EFFECT OF PAVEMENT THICKNESS ON SUPERPAVE MIX PERMEABILITY AND DENSITY

WisDOT Highway Research Study 0092-02-14

THIRD DRAFT FINAL REPORT

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CHAPTER ONE

INTRODUCTION

1.1 Background and Problem Statement

It is well recognized that density that could be achieved in the field is significantly affected by the maximum aggregate size of aggregates, the gradation, and the lift thickness. It is also well known that permeability of asphalt mixtures is a function of aggregate gradation, density achieved, and distribution of air voids. With the shift in mixture designs to Superpave methods, gradations on the coarse side of the maximum density line are being widely recommended and used. These gradations are unique in their densification characteristics and are claimed to be more permeable. It is not clear whether this trend is due to changes in the air voids distribution, the lower densities being achieved, or both. This trend is of special importance to Wisconsin as the shift to Superpave mixtures is underway. Recent studies have also shown that permeability is a directional property such that orientation of the aggregates, which is affected by lift thickness and level of compaction, has a significant effect on total permeability.

Wisconsin has traditionally used 75-mm dense graded HMA overlays placed in two lifts, a 44-mm binder lift and a 31-mm surface lift. These lift thicknesses are based on the traditional rule that lift thickness be twice the maximum aggregate size. Starting in the year 2000, Wisconsin has decided to move from Marshall design to Superpave mixture design. Superpave mixes tend to be harder to compact. Additionally, Superpave guidelines recommend the lift thickness be a minimum of 3 times the nominal maximum aggregate size. This move poses two problems for Wisconsin: 1) the current design criteria for overlay thickness will result in thin-lifts of Superpave mixes that the AASHTO Lead States Committee has reported as having problems with pavement permeability and achieving pavement density, and 2) these mixes may be impossible to compact in the field contributing to the permeability problem, even though they meet laboratory density criteria.

There is a need, therefore, for a study to evaluate the potential problems and to establish procedures to relate laboratory density to field study and to estimate or measure permeability during mixture design. The study also needs to define the relationship between lift thickness and aggregate gradations that will minimize the densification problem and address the permeability concerns.

There is a previous study conducted by the University of Wisconsin-Madison evaluating the effect of lift thickness to maximum aggregate size ratio on compaction of Superpave mixtures (WHRP Report # 03-02). This study showed the effect of size to the thickness ratio and indicates that density is highly dependent on size and gradation in the laboratory when the Superpave Gyratory Compactor is used. It was also found that the optimal size to thickness ratio varies according to the angularity and source of the aggregates. The extrapolation of the laboratory results to the field was not achieved and in the field the limited study could not show the same trend observed in the laboratory. Also the project did not cover the permeability of mixtures which is an important property that could affect pavement layers integrity and performance. Thus the field validation of factors affecting density and permeability is the challenge that was addressed in this new project, which is the subject of this report.

1.2 Literature Review

This section summarizes information on previous research related to the permeability and density of hot-mix asphalt (HMA) mixture within the scope of the project. The fundamental concepts of permeability are described as a background for the permeability measurement. The equipment and test methods currently employed by various agencies in determining the permeability both in the laboratory and in the field study are reviewed, and the one considered the most appropriate was selected for the research. Critical factors that need to be considered in evaluating the permeability are discussed, and the required levels of each critical factor in the experimental design are indicated. The study of the correlation between lab and field permeability values based on previous studies is also summarized in this section. Additionally, the critical factors affecting density in the field, which is considered to be the main factor influencing permeability, are described.

1.2.1 Fundamental Concepts of Permeability

In 1856, Henry Darcy, a French civil engineer, established the fundamental concept of permeability. His concern in the public water supply led him into the design of permeable filter sands for water purification. He investigated the flow of water through sand, and the parameter of his experiment was called the coefficient of permeability or the permeability. The permeability is the rate of water flow and is proportional to the hydraulic gradient. The permeability in Darcy's law can be written as:

$$Q = k \cdot i \cdot A = k \cdot \frac{\Delta H}{L} \cdot A \tag{1.1}$$

where Q is the rate of flow, k is the permeability, i is the hydraulic gradient, ΔH is the head loss across specimen, L is the length of specimen, and A is the cross-sectional area of specimen perpendicular to direction of flow. The total head loss is the sum of elevation head loss (H_e) and pressure head loss (H_p), where the pressure head is related to the water pressure (u). Figure 1.1 shows the fundamental concept of the flow of water through a specimen.

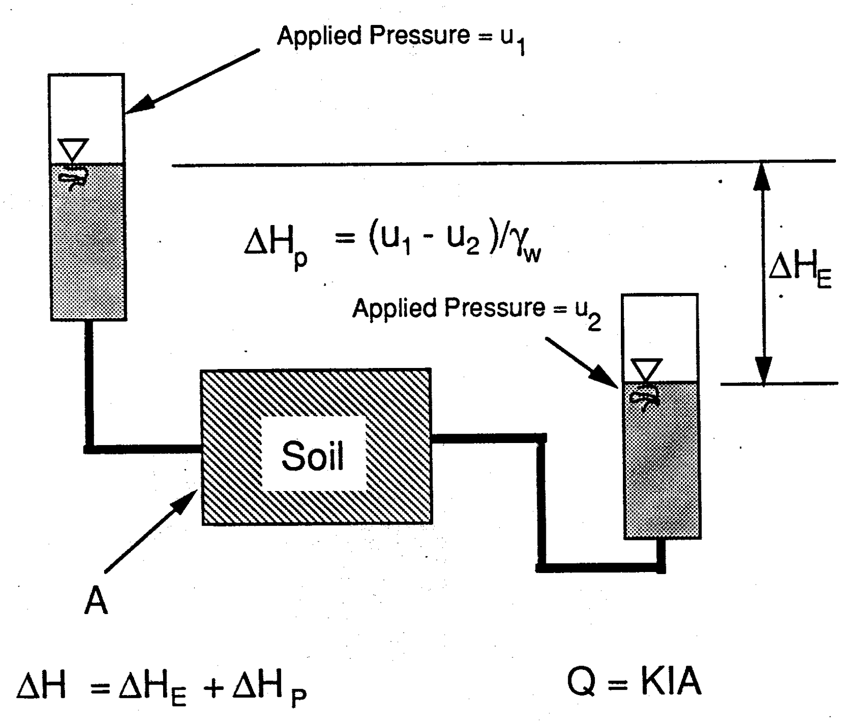


Figure 1.1 Fundamental Concept of Permeability Testing

Darcy's law is valid for the flow through most granular materials. As long as the flow is laminar, a linear relationship between specific discharge and hydraulic gradient is found. Under the turbulent flow, the water flow paths are more tortuous; therefore, the relationship becomes nonlinear. According to Darcy's law, there are two testing methods used to measure the permeability, a constant head method and a falling head method (falling head or falling headwater-rising tailwater).

The system for constant head method can maintain a constant hydraulic pressure or head to within ±5%, and the head loss across the specimen is held constant. As shown in Figure 1.2(a), the water is allowed to flow through specimen. After an adequate amount of water is collected over the time of test, the flow rate Q is determined. The permeability is then calculated by:

$$K = \frac{QL}{Ah} \tag{1.2}$$

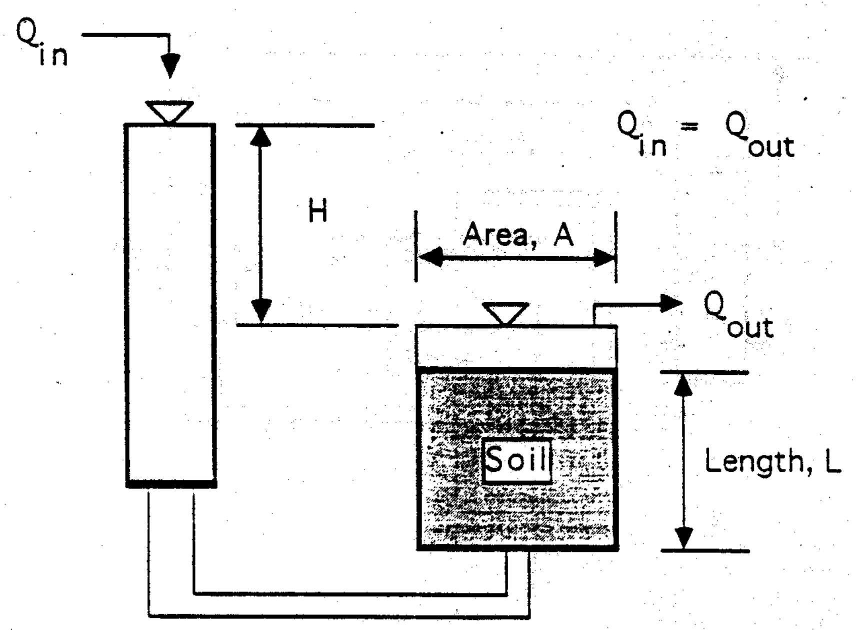
where Q is the flow rate, L is the length of specimen, A is the cross-sectional area of specimen, and h is the constant head shown in Figure 1.2(a).

In the falling head method, the head in the standpipe and the time are measured. The permeability is then calculated by:

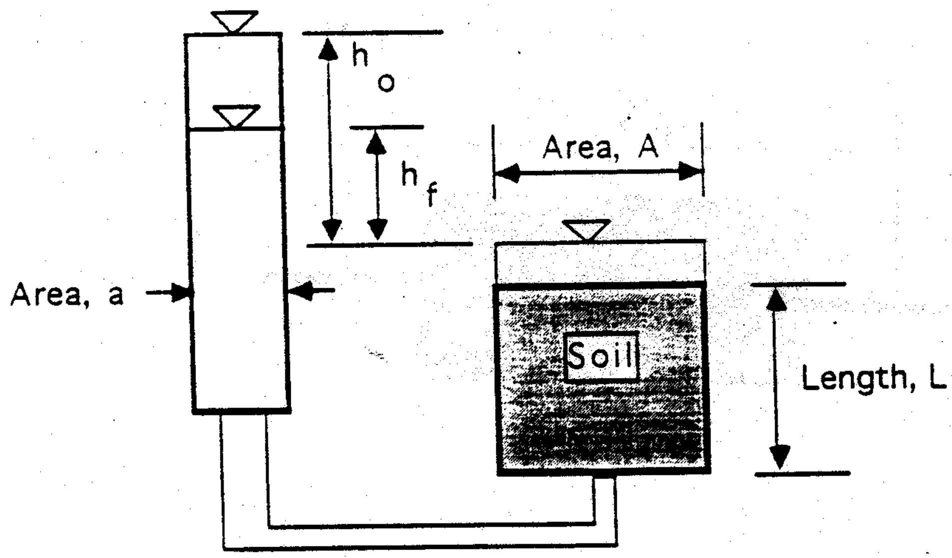
$$K = \frac{aL}{At}\ln\left(\frac{h_o}{h_f}\right) \tag{1.3}$$

where a is the cross-sectional area of the stand pipe, L is the length of specimen, A is the cross-sectional area of specimen, t is the time required for the head to fall from h_o to h_f, h_1 is the water head at beginning of test, and h_2 is the water head at end of test (Figure 1.2 (b)).

The literature review indicates that the constant head method is more appropriate for measuring high permeable materials ($K > 10^{-3}$ cm/s), and the falling head method is more appropriate for measuring less permeable materials ($K < 10^{-3}$ cm/s). The falling head method is, therefore, a better alternative for measuring the permeability of asphalt mixtures, for which the typical values of permeability are in the range of 10^{-3}- 10^{-5} cm/s.



a) Constant Head Method



b) Falling Head Method

Figure 1.2 Two common methods for measuring permeability

Air permeability testing has also been utilized to quantify the permeability of dry, porous media. Early applications were based on the falling head water permeability tests, with a pressurized air vessel substituting for the imposed water head and the quantity of air flow through the porous media related to the pressure drop in the air supply. To calculate values of permeability using air flow, the form of Darcy's law commonly used in falling head techniques must be manipulated. The following equation provides the intrinsic or absolute permeability (Collins 1961, Hillel 1998, Weaver 1955) of the porous media being tested:

$$K = \frac{VL\mu}{ATP_a} \ln\left(\frac{p_1}{p_2}\right) \tag{1.4}$$

where K is the intrinsic (absolute) permeability, V is the volume of the pressure chamber, μ is the dynamic viscosity of air, A is the cross-sectional area of sample, T is change in time (seconds) over pressure loss, P_a is the atmospheric pressure, p_1 is the air pressure at the beginning of time measurement, and p_2 is the air pressure at the end of time measurement. The intrinsic permeability can be equated to a measurement of the average diameter of the effective void pathways (Collins 1961, Hillel 1998). This value of permeability is considered absolute because it is independent of the fluid flowing through the porous medium.

The intrinsic permeability can be expressed as an equivalent hydraulic conductivity (commonly referred to as permeability) through the following relation (Collins 1961, Hillel 1998, Weaver 1955):

$$K = k_w \frac{\mu_w}{\rho_w g} \tag{1.5}$$

where K is the intrinsic (absolute) permeability, k_w is the hydraulic conductivity (permeability), μ_w is the dynamic viscosity of water, ρ_w is the mass density of water, and g is the acceleration due to gravity. Equations 1.4 and 1.5 may be combined to yield a direct equation for calculating the hydraulic conductivity for air permeameter measurements as:

$$k_w = \frac{VL\mu\rho_w g}{ATP_a\mu_w} \ln\left(\frac{p_1}{p_2}\right) \tag{1.6}$$

1.2.2 Selection of Equipment and Methods of Measurements

Researchers in the past have identified several equipment and test methods to measure the permeability of asphalt mixture both in the laboratory and in the field. The existing equipment and their test methods are summarized in Table 1.1.

Table 1.1 Equipment and test methods used to measure the permeability of asphalt mixture

Measurement	Equipment and Method	Testing Factors	Researcher	Comments
Laboratory Permeameter	Falling-head type permeameter	Degree of saturation (significant effect)	Vallerga and Hicks (1968)	Apply back-pressure to ensure saturation
	- Permeameter (Karol-Warner) - Falling-head method - FDOT Procedure	- Confining pressure (insignificant effect) - Testing time (insignificant effect)	Hall et al. (2000)	- Widely used for HMA - Some shortcomings found in FDOT method (no method ensure saturation)
	Flexible-wall, dual mode permeameter, developed in LTRC	None	Huang et al. (1999)	- Good for determining the permeability when Darcy's Law is not valid - Darcy's Law is not valid for high effective porosity, and high permeability
	- Flexible-wall permeameter - Falling-head rising-tail method - ASTM D 5084 (Method C)	- Degree of saturation (significant effect) - Hydraulic gradient (insignificant effect) - Sidewall leakage (significant effect)	Kanitpong et al. (2001)	Apply back-pressure to ensure saturation
Field Permeameter	NCAT permeameter	None	Cooley, (1998)	Ease of use, repeatable, correlated to laboratory results.

Two-Way Permeameter	Two-Way Permeameter	Degree of permeability anisotropy of compacted or undisturbed soil	Moore, (1979)	

Among these equipment and methods, the flexible-wall falling-head permeameter developed by Florida Department of Transportation (FDOT) have been commonly employed as a laboratory permeameter for asphalt mixtures (Mallick et al. 2001 and Hall et al. 2000). This method, developed in 2001, is widely known as the ASTM PS 129-01 (*Standard Test Method for Measuring the Permeability of Asphalt Mixtures*). However, there are some shortcomings associated with this method (Kanitpong et al. 2001). The concern about degree of saturation is very important, because the permeability can vary in the orders of magnitude as the degree of saturation of asphalt mix is varied. As the degree of saturation decreases, the permeability decreases as well, since water cannot flow through air bubbles in the voids. Since the Florida method (PS 129-01) has no method to ensure saturation or to control the degree of saturation, the permeability obtained from the Florida method cannot be directly applied to describe the capability of HMA to transmit fluid. More importantly, the Florida method does not ensure a consistent degree of saturation for HMA mixtures. That is, different degrees of saturation can be obtained with the Florida method when testing specimens having different characteristics. Because of the shortcomings of the Florida method, other reliable methods were considered for this research.

Another commonly used method is the ASTM D 5084 (*Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible-Wall Permeameter*). This method was selected and used by Kanitpong et al. (2001) for asphalt mixtures because it is one of the most widely used in North America for measuring the saturated permeability of porous materials having saturated permeability less than or equal to 10^{-3} cm/s. In addition, the factors listed as shortcomings in the Florida method were considered when ASTM D5084 was developed. The ASTM D 5084 method allows applying the backpressure saturation procedure that ensures the saturation, as well as produces consistent and repeatable data, which could not be obtained with the widely used Florida method. The ASTM D 5084 was, therefore, selected in the laboratory study of this research study.

For the field study, the field permeameter that was designed and developed by the National Center for Asphalt Technology (NCAT) was selected. The literature reviewed indicated that this kind of permeameter can give a good correlation with the laboratory permeameter, is repeatable, and is easy to use (Cooley 1998). The study from WPI (2000) has raised some concerns about of the NCAT device; hence a modified permeameter was developed by using NCAT device as a model. In addition to using the modified version of the NCAT device, the research team decided to take pavement layer cores at the same test location as the field-testing is conducted and to conduct the laboratory permeability on the cores taken from the field for direct comparison.

1.2.3 Factors Affecting Lab and Field Permeability of Asphalt Mixtures

Several researchers identified a number of factors that can affect the permeability of gyratory-compacted and field-compacted asphalt mix specimens. Air void content, effective voids, gradation, NMAS, aggregate source, VMA, thickness, and void pathways are among the mostly mentioned factors. The summary of these factors including the range of critical values, the relationship to the permeability, and the supporting researchers for laboratory studies and for field studies are summarized in Table 1.2 and Table 1.3, respectively.

Table 1.2 Factors Affecting Permeability of Asphalt Mixtures in Laboratory Study

Variable Name	Range Of Values	Comments	Researcher
Air Voids	N/A	Higher air void content, higher permeability (affected by asphalt content)	McLaughlin, and Goetz (1955)
	Above 5%	Good correlation with permeability	Gilbert, and Keyser (1973)
	N/A	- Higher air void content, higher permeability. - Size and connectivity are important. - Higher air voids, high possibility of air voids connectivity.	Abdullah et al. (1998)
	At 7%, $K \approx 10^{-4}$ cm/s	Higher air void content (low density), higher permeability.	Westerman (1998)
	At 4%, $K \approx 10^{-7}$ cm/s At 6-8 %, $K \approx 10^{-5}$-10^{-3} cm/s	- Significant Effect. - Higher air void content, higher permeability.	Kanitpong et.al (2001)
	At 4%, $K \approx 8.5\text{x}10^{-7}$ cm/s At 8 %, $K \approx 1.2\text{x}10^{-4}$ cm/s	- Significant Effect - Higher air void content, higher permeability.	Kanitpong et.al (2002)
Gradation	Dense-graded mix has lower permeability than gap-graded mix.	- No relationship b/w permeability and durability - Dense-graded mix is not the best for durability. Asphalt film thickness is more important.	McLaughlin, and Goetz (1955)
	Coarser mixes, higher permeability	Coarser mixes, larger void sizes.	Abdullah et al. (1998)
	Open-graded mix, $K \approx$ 0.27-1.48 cm/s LA Type 508 open graded drainable base, $K \approx$ 2.47-3.61 cm/s Dense-graded mix, $K \approx$ $3\text{x}10^{-4}$-$116\text{x}10^{-4}$ cm/s	Significant effect	Huang et al. (1999)

	Finer graded, lower permeability (at constant air voids)	- Significant Effect - S-shaped gradation gives higher permeability	Kanitpong et.al. (2001)
	At air voids < 8%, Fine graded mix has higher permeability than coarse graded mix at a given air void content	- Significant Effect	Kanitpong et.al. (2002)
NMAS	N/A	No significant effect	Kanitpong et al. (2002)
Aggregate Source	Basalt > Granite > Limestone	Higher porosity of aggregate, higher permeability (at constant level of asphalt content)	Abdullah et al. (1998)
	N/A	Significant effect	Kanitpong et al. (2002)
VMA	N/A	No relationship with permeability	James (1965)
	N/A	Higher VMA, higher permeability	Abdullah et al. (1998)
	N/A	No relationship with permeability	Kanitpong et.al (2001)
Thickness	N/A	Correlated with air voids (limited data)	Kanitpong et.al (2001)
	N/A	Decrease in permeability with increase in thickness	Mallick et al. (2001)
	N/A	No significant effect (From statistical view point)	Kanitpong et al. (2002)
Void Pathways	Higher connectivity, higher permeability (at constant air voids content)	- Not straight and vertical, but convoluted towards to the perimeter of specimens. - Field cores have higher interconnectivity than SGC samples.	Hall et al. (2001)

Table 1.3 Factors Affecting Permeability of Asphalt Mixtures in Field Study

Variable Name	Range Of Values	Comments	Researcher
Air Voids	At 10%, K ≈ 150 ml/min (2 cm/s)	- Permeability not exceed 150 ml/min will be low enough to prevent access moisture.	Zube (1962) (Field test)
	At 7%, K ≈ 10^{-3} cm/s (for coarse-graded)	- Permeability limit not more than 10^{-3} cm/s is suggested in the in-place Superpave mix pavement permeability - Air void structures in gyratory sample, and field compacted core are not comparable (at same air voids level)	Choubane et al. (1998) (Laboratory test of field cored sample)
	At 7%, K increased significantly	Significant effect	Mallick et al. (2001)
	The critical values of air voids depend on NMAS 7.7% for 9.5 mm NMAS 7.7% for 12.5 mm NMAS 5.5% for 19.0 mm NMAS 4.4% for 25.0 mm NMAS (for coarse-graded Superpave mix)	Significant effect	Cooley et al. (2001)
Gradation	Coarse-graded has higher interconnectivity of voids.	- In-place air voids of coarse-graded appear to have greater interconnectivity than fine-graded (at same air voids level)	Choubane et al. (1998) (Laboratory test of field cored sample)
	No difference occurred between coarse and fine graded mixes	- Can not compare because higher air voids in fine graded mix, and different in thickness	Mallick et al. (2001)
NMAS	At air voids = 6%, and for coarse-graded, 9.5 mm NMAS, K ≈ $6x10^{-5}$ cm/s 12.5 mm NMAS, K ≈ $40x10^{-5}$ cm/s 19.0 mm NMAS, K ≈ $140x10^{-5}$ cm/s 25.0 mm NMAS, K ≈ $1200x10^{-5}$ cm/s	- Significant Effect - At given air void content, permeability increased by one order of magnitude as the NMAS increased.	Mallick et al. (2001)

	For coarse-graded Superpave mix, 9.5 mm NMAS, K ≈ 100×10^{-5} cm/s 12.5 mm NMAS, K ≈ 100×10^{-5} cm/s 19.0 mm NMAS, K ≈ 120×10^{-5} cm/s 25.0 mm NMAS, K ≈ 150×10^{-5} cm/s	Significant effect	Cooley et al. (2001)
Aggregate Source	None	None	None
VMA	None	None	None
Thickness Min lift thickness ≥ 51 mm, or 4 times NMAS	4 times NMAS (required for coarse-graded Superpave mixes) Adequate density results in adequately low permeability	- Because criteria for fine-graded Marshall mixes may not be adequate for coarse-graded Superpave mixes. Westerman (1998)	Choubane et al. (1998) (Laboratory test of field cored sample)
		Significant effect	Cooley (2001)

Based on the summary, air void content was found to be the most critical factor that can affect the permeability both in the laboratory and in the field study. As the air voids increase, the permeability also increase (McLaughlin and Goetz 1955, Zube 1962, Westerman 1998, Choubane et al. 1998, Gilbert and Keyser 1998, Abdullah et al. 1998, Kanitpong et al. 2001, Mallick et al. 2001). However, a recent detailed study indicates that in measuring the permeability of asphalt mixtures, the total volume of voids is not as important as the connectivity of voids (Huang et al. 1999). Therefore, the relationship between the effective voids content, which is the ratio of voids to be drained under gravity to the total volume of mixture, and the permeability, was also evaluated by some of the researchers (Huang et al. 1999, Cooley et al. 2002, Al-Omari et al. 2002).

Gradation also plays as a significant role in the permeability. Coarse graded mix contains larger void sizes, and has higher possibility for connectivity of voids, hence resulting in higher permeability (McLaughlin and Goetz 1955, Choubane et al. 1998, Huang et al. 1999, Abdullah et al. 1998). S-shaped gradation was also found to have higher permeability compared with other coarse graded mixes (Kanitpong et al. 2001).

While the NMAS was not found to have a significant effect on the permeability of laboratory compacted specimens (Kanitpong et al. 2001), it significantly affects the field permeability (Mallick et al. 2001). This result could point out the problem of the discrepancies between permeability of laboratory compacted specimens and the field specimens.

Aggregate source is shown to have a significant effect on the permeability (Abdullah et al. 1998, and Kanitpong et al. 2002). Aggregate shape affects size of voids, shape, and connectivity of voids, and hence, directly influences the permeability. However, there exist the inconsistent results regarding to the effect of percent VMA on the permeability in the literature.

Lift thickness is also a questionable factor. Some researchers stated that the lift thickness significantly affects in the field density and permeability (Choubane et al. 1998, Mallick et al. 2001). Unfortunately, this finding could not be observed as a significant factor for laboratory compacted specimens (Kanitpong et al. 2002). It can only be concluded that further study is necessary to investigate the effect of lift thickness, and the correlation between the laboratory and field specimen need to be evaluated.

Void pathway was indicated as an important variable that need to be addressed. Hall (2000) found that most of void pathways are not straight and vertical, but convolute towards the perimeter of specimens. In addition, he also found that the field-cored specimens have higher connectivity of voids than the gyratory compacted specimens.

1.2.4 Relationship Between Lab and Field Measurements

This section includes the discussion from previous study that evaluating the relationship between lab and field permeability, and the relationship between the permeability of field cores and gyratory compacted specimens.

Relationship Between Lab and Field Permeability Measurements

Cooley's research (2002) includes the comparison study between the lab and field permeability measurement (Cooley et al. 2002). The laboratory permeability tests were conducted on cores cut from the pavement sections for which the in-place field permeability was measured. They found that the relationship between field and laboratory permeability results is not simple. At permeability less than 500×10^{-5} cm/sec, the lab permeability is higher than the field permeability. However, they indicated that this result was not as expected, since the field results should provide higher permeability because water can flow from the field permeameter in any direction, while laboratory permeameter restricts water to flow in only one direction. The field test was, therefore, expected to obtain higher permeability. A possible explanation for this result is that, at permeability above 500×10^{-5} cm/sec, asphalt mixes have a high percentage of interconnected air voids. In the field, these interconnected air voids may or may not be of a length that they allow water to flow. On the other hand, the laboratory permeameter may allow a single large interconnected air void that extends within the asphalt specimen and result in high laboratory permeability.

According to their conclusion on the relationship between lab and field permeability measurements, it is indicated that both methods provide similar results at permeability values that are not excessive. Cooley et al. (2001) suggested that field permeability values should be less than 150x10^{-5} cm/sec. Their study suggests that the field permeameter provide reasonable results and are comparable to the controlled lab permeability test method. The advantages of field permeameter are that it provides more rapid test results and is nondestructive.

Relationship Between Permeability of Field Cores and Gyratory Compacted Samples

Because of the differences in air void distribution of the laboratory and field compacted samples, similar interconnected void structures are unlikely. Cooley et al. (2002) conducted a study to evaluate the relationship between permeability and density with lab and field compacted mixes. Two techniques were used in their study: laboratory permeability measurements on samples compacted using the gyratory compactor and water absorption determined with AASHTO- T166 and the Corelok device.

In Cooley's study, the Superpave Gyratory Compacted (SGC) samples could not be produced at the exact same air void levels as the field cores, therefore, the relationship between air voids and lab permeability was determined for each of the three NMAS. The 9.5 mm mix indicated that there is a strong relationship between air voids and permeability. However, the relationships between permeability and density are different between two specimen types (lab-compacted vs field compacted). The results of field specimens show higher permeability at a given air void content than the lab specimens. For the 12.5 mm and 19 mm NMAS mix, there is a good relationship between density and lab permeability for both the field cores and the SGC specimens. The limited data in their study indicated that SGC samples could be used to estimate the field compaction level required to produce an impermeable mix.

In addition, the relationship between water absorption and permeability was evaluated to identify a parameter that would indicate potential permeability problems in the field. It seems intuitive that the percentage of water permeable voids should be related to the available flow paths for the water and in turn to permeability. The results from this study showed a reasonable relationship between water absorption during AASHTO T-166 and water permeable voids from Corelok testing and permeability results (both field and lab). This may be used as a quick screening test to identify pavements that may be permeable.

1.2.5 Factors Affecting Density of HMA During Construction

Several studies have been reviewed for identifying the important factors that could affect the reaching of required density of HMA during the construction. Some of these factors will be considered as independent variables in the experimental design for this study, and they are summarized as shown in Table 1.4.

Table 1.4 Summary of factors affecting density of HMA during construction

Variable	**Type**	**Comment**
Gradation	Fine Coarse	Quantitative measure need to be defined between fine and coarse materials used in the mixture
Aggregate Angularity	Crushed aggregate (angular particles) Natural aggregate (round particles	Quantitative measure, i.e., % crushed faces and % crushed particles needed to be determined
Thickness	Thickness to NMAS Ratio	Study by Paye 2001
Compaction Force	N/A	Resultant and pressure applied to the mat are measured with simple statics and geometry

Roller Types	Vibratory Roller Pneumatic Tire Roller Static Steel Roller (Cold Roller)	Specific contribution of certain roller types to densification under varying mat thicknesses is important (Paye 2001)
Base Type	Concrete Milled Asphalt CABC Rubblized Concrete	Found significant in (Paye 2001)
Temperature	N/A	Decreasing temperature increases the resistance of the asphalt mix to densification

1.2.6 Summary of Literature Review

The review of literature on permeability measurement of HMA both in the laboratory and in the field has resulted in the following action items:

- Selecting the flexible-wall permeameter using the ASTM D5084 method, and the NCAT permeameter for measuring laboratory and field permeability, respectively, in this study.
- A number of variables that could affect the density and permeability of HMA are considered and included in the experimental design.
- The findings of some literature that included the permeability and density criteria of HMA will be compared to the final results of the study.

1.3 Research Objectives

The objectives of this research are as follows:

1. Determine the influence of maximum aggregate size, lift thickness, and aggregate source on the density and permeability of asphalt mixtures designed according to the Superpave criteria.

2. Develop guidelines for the selection of pavement layer thickness based on nominal maximum aggregate size and gradation for use in Wisconsin.
3. Evaluate the effect of void characteristics, arrangement, and interconnectivity on permeability.
4. Recommend laboratory and field permeability testing procedures and equipment for design and quality control of Superpave mixtures in Wisconsin.
5. Recommend permeability and density criteria for Superpave mixture designs in Wisconsin based on traffic, lift thickness, field drainage and moisture conditions.

1.4 Research Methodology

The research methodology used is illustrated in Figure 1.3. The research plan is divided into seven major tasks, which are described as follow:

Task 1: Literature Review on Density and Permeability of Superpave Mixes

A literature review was conducted to document published information and results of studies conducted at the national and regional level as related to this project. The result of this task was summarized in section 1.2 in this chapter. According to the literature review study, the most appropriate equipment and methods for measuring density and permeability were selected for this project. The critical factors that need to be covered in the laboratory and in the field study were also identified and the required levels of each critical factor in the experimental design were selected as discussed in the next section.

Task 2: Identify critical variables and select commercial HMA plants with consistent aggregate sources

In this task, the critical variables that affect the density and permeability of HMA were initially defined and used in the experimental design. The research team, in collaboration with the Wisconsin DOT and the representative of the asphalt paving industry, then selected HMA plants with consistent aggregate sources. The major aggregate sources representing the most widely used aggregates in Wisconsin pavements were selected. Other critical variables such as gradation and nominal maximum aggregate size were also considered in the selection of Superpave mix and materials used in the study.

Task 3: Identify projects for field comparisons

In this task a set of projects were selected that allow measuring the effect of different variables identified in the experimental results. These projects include Superpave mixtures with different nominal maximum aggregate size, gradations, aggregate sources, lift thickness and sub-surface layers. The selection was based on a review of WisDOT projects and other projects that the asphalt industry is involved in. The characteristics of each project were documented first, and based on specific criteria; the projects were ranked and matched with required factors to be studied. The highest ranked projects were selected and reviewed with the members of the flexible pavement TOC to finalize the list and contact the contractors involved.

Task 4: Conduct Field and Laboratory Studies

In the field study, the in-place densities were measured by using nuclear gauges, and the field permeability was performed immediately after the density was measured. The field permeability was measured by using a falling-head permeameter similar to

NCAT device. The field cores were then taken to laboratory after the permeability was completed. The loose mix from each project was taken to the lab for producing the laboratory compacted specimens. In the laboratory study, the Superpave gyratory compactor (SGC) was used to compact the specimens from loose mixes at the same density as the field cores. The lab permeability was then measured for field cores and lab-compacted specimens. The relationships between field permeability, lab permeability of field cores, and lab permeability of lab-compacted specimens were determined from the results obtained in this task.

Task 5: Air and Water Permeability Studies

This task includes the field permeability tests conducted on newly constructed asphalt pavements using the NCAT water permeameter and the ROMUS air permeameter. The ROMUS air permeameter was designed and constructed by Jay Schabelski during this study to provide a more efficient alternate to the NCAT device and to be suitable for field testing of asphalt pavement types investigated during this study. This device was furnished to the project team and a comparison of field permeability results obtained with both devices was established in this task. It is believed that the ROMUS air permeameter may be better suited to in-place permeability testing of asphalt pavements as the device produced more efficient and repeatable measures than the NCAT water permeameter for all pavement types investigated.

Task 6: Analyze Data and Prepare Guidelines

According to the results in Task 4 and 5, the data was analyzed and the guidelines were prepared. Statistical analysis was used to establish the relationship between permeability, density and the controlled variables. These variables included lift thickness, nominal maximum aggregate size, gradation, aggregate source, sub-surface layers, and other factors that might be found through the research. A relationship between permeability, density and lift thickness to aggregate size was evaluated.

Task 7: Prepare and Submit Final Report

This final report was written to include work conducted in Tasks 1 to 6 of this resercah study. It also includes the guidelines for how to select the effective pavement thickness corresponding to the permeability and density criteria. The primary product of this research is a table describing the relationship of recommended Superpave pavement thickness, nominal maximum aggregate size and gradation to the permeability and density of Superpave mixes. The second product is a recommendation for the laboratory testing procedures to predict the permeability in the field. These products are included in a final report that reflects the basis for recommended guidelines and that documents the research effort.

1.5 Experimental Design

To accomplish the research objectives, the experimental design selected included the following experimental variables:

Response Variables

- Density
- Permeability

Controlled Variables

- Sub-surface layers: Strong Base (Concrete) and Weak Base (HMA and CABC)

- Aggregate sources: Limestone and Granite
- Gradation: Coarse and Fine
- Nominal maximum aggregate size (NMAS): 9.5 mm, 12.5 mm, 19 mm, 25 mm
- Lift Thickness to NMAS ratio: In range of 3-5

1.6 Summary

This report is organized into five chapters. Chapter 1 includes the background, problem statement, literature review, objectives, research methodology, and research scope. Chapter 2 includes the field data analysis and discussions. The results from the field study are described in details and the effect of different variables on the field density and permeability is determined. The guidelines for the selection of pavement layer thickness based on nominal maximum aggregate size and gradation are also developed in this chapter. Chapter 3 includes the results of the laboratory study. The relationship among the field permeability, lab permeability of filed specimens, and lab permeability of lab-compacted specimens is evaluated. The laboratory testing procedure for predicting permeability in the field is also recommended in this chapter. Chapter 4 contains the analysis and comparison of the air and water permeability results. Chapter 5 includes a summary of findings, the conclusions from this study, and the recommendations for future research.

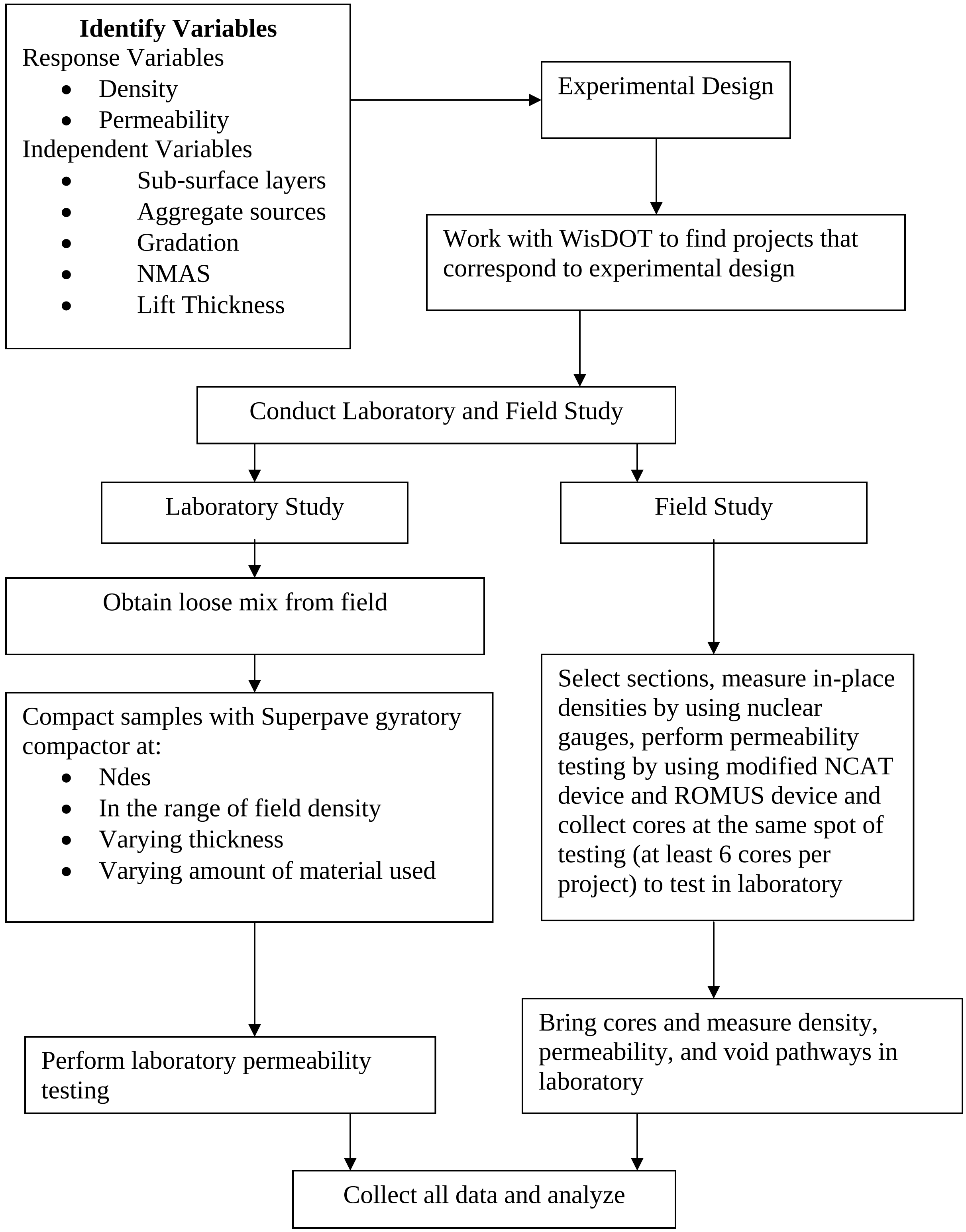


Figure 1.3 Research Methodology

CHAPTER TWO

FIELD STUDY

2.1 Introduction

The field portion of the study was designed to determine factors that influence density and permeability of WisDOT asphalt pavements designed according to Superpave criteria. From the literature review, variables thought to have an effect on density and permeability were selected. Three primary variables evaluated between projects were: (1) Gradation (coarse and fine), (2) Source (gravel and limestone), and (3) Base Stiffness (rigid and flexible). A total of eight project combinations allowed a direct evaluation of these variables: [2 gradations x 2 sources x 2 base types] = 8 projects. Ndes was an additional between-project variable, but was not directly controlled during project selection. Six variables evaluated within each project, included: (1) Nominal Maximum Aggregate Size (NMAS), (2) layer thickness, (3) layer thickness-to-NMAS ratio (t/NMAS), (4) density, (5) fine-graded mix aggregate ratios, and (6) roller set-up.

Gradation was classified coarse as follows:

25.0-mm NMAS: Less than or equal to 25% passing the 2.36-mm sieve

19.0-mm NMAS: Less than or equal to 30% passing the 2.36-mm sieve

12.5-mm NMAS: Less than or equal to 35% passing the 2.36-mm sieve

9.5-mm NMAS: Less than or equal to 40% passing the 2.36-mm sieve

Although there are several types of aggregate sources used in Wisconsin highway construction, only gravel and limestone were selected because of their widespread use and limited resources available for the study. The field study balanced statistical requirements with resource availability, and it was concluded that it was more beneficial to have fewer sources and a greater amount of testing within each source. When comparing the physical shape of the two aggregates, gravel has a more round, cubical appearance, while limestone has a sheared-plane, multi-faced appearance.

Base type was classified rigid if it was Portland Cement Concrete (PCC), and flexible if it was asphalt pavement (milled or existing) or crushed aggregate. No testing was performed on rubblized PCC bases.

Table 2.1 provides a matrix of projects with each specific variable combination. It was not possible to collect data from all variable combinations, in particular projects having a gravel source and rigid base. Two gravel/rigid candidate projects were warranted pavement and WisDOT staff allowed no coring, thus precluding those projects from the study. Findings from the 2002 data allowed the research to screen the most significant variables, and allow more detailed experimentation during the 2003 data collection phase. An analysis of field data collected from the 2002 paving season found a wide amount of variation in field data, and doubling the combinations allowed greater resolution in the data. For several variable combinations, two projects were used for data collection to strengthen the data set and analysis.

Table 2.1 Project Matrix

Project (1)	Gradation (2)	Source (3)	Base (4)	NMAS, mm (5)	Ndes (6)
Wis. Ave.	Fine	Limestone	Rigid	19, 12.5	75
I-894				19, 12.5	100
USH-10	Fine	Limestone	Flexible	19, 12.5	60
STH-21				19, 12.5	100
---	Fine	Gravel	Rigid	---	---
---				---	---
STH-23	Fine	Gravel	Flexible	19, 12.5	75
USH-8				19, 12.5	75
I-43	Coarse	Limestone	Rigid	19	100
USH-20 (ILL.)				19, 9.5	70
I-94	Coarse	Limestone	Flexible	25	125
---				---	---
---	Coarse	Gravel	Rigid	---	---
---				---	---
STH-17	Coarse	Gravel	Flexible	25	75
---				---	---

Within each project, variation in thickness and density were produced from natural field construction variation or fabricating the variation at locations within the project by adjusting construction operations. NMAS was varied by testing different layers within a project. However, on both the I-94 and STH-17 coarse-graded projects, a fine-graded surface mix was paved and no testing was performed on this layer. Roller operations were documented, including such factors as roller type (steel drum or pneumatic tire), vibratory compaction (yes or no), mat temperature, and number of passes.

2.2 Equipment and Methods

Field data collection for each project involved five primary steps: (1) coordination and test site identification, (2) density growth testing, (3) NCAT permeameter testing, (4) air permeameter testing, and (5) pavement coring. Field data collection occurred the day of paving, or a few days after paving before traffic was permitted on the test sites. All testing was conducted before rainfall.

2.2.1 Coordination and Test Site Identification

Projects were selected and coordinated with WisDOT and contractor personnel. Effort was made to conduct testing with minimal disruption to scheduled construction activities. Testing time on a project normally required a minimum of four hours per layer. Contractor mix designs and loose mix were collected for the laboratory component of this study (see laboratory section of report).

Six test sites were selected for each NMAS layer within a project. For example, STH 23 had six test sites in the 19-mm NMAS bottom layer, and six test sites in the 12.5-mm NMAS top layer. A minimum of six test sites was chosen per layer to optimize the number of data points within the time and resource constraints of field testing. On several projects, more than six test sites per layer were field tested to guard against core damage, ensure thickness and density variation, or other factors.

Two variables controlling test site selection were layer thickness and density. The paving crew provided an estimate of planned layer thickness for the day's paving, and sites producing the widest range and median were selected. Two test sites each were then chosen from the minimum, median, and maximum thickness areas. Test sites with t/NMAS ratios below 3 and above 5 (outside the range in Subsection 405.3.9.2 of the Specifications) were given priority in an effort to broaden the data range and help understand this effect on density and permeability. In many cases, initial test sites were discarded due to insufficient density (generally below 90%), surface segregation, or an uneven surface profile from roller wheels. Data on the USH-41/Lannon Road Intersection project was discarded due to median density values below 90%, segregation, delayed paving schedule, and other project factors. Compacted layer thickness was estimated from the loose layer thickness. Maximum surface slope for all test sites was limited to 4%.

2.2.2 Density Growth Testing

Density growth testing was conducted to measure the compactability of the pavement layer from typical project variables, such as NMAS, layer thickness, roller type, change in density from screed to finish roller, mat temperature, and vibratory application. Multiple 15-second readings were taken with the nuclear density gauge at each test site behind the paver screed and after series of roller passes. Vibratory setting (on or off) and pavement temperature were recorded after the roller pass. In several cases, it was not possible to collect data after every pass due to safety concerns.

2.2.3 NCAT Permeameter Testing

After density growth testing, the pavement was allowed to cool naturally for permeability testing with the NCAT permeameter device. The pavement was generally tested below a surface temperature of 125°F to ensure an adequate seal. The permeameter was centered within the rectangular base used for nuclear density growth testing, sealant was applied between the pavement and permeameter base, a 20-kg weight was added to prevent uplift force from the water head, then the pavement was saturated. Several trials were conducted at each test site for repeatability information and to incorporate testing variability into the analysis.

2.2.4 Air Permeability Testing

Air permeability testing was conducted using the ROMUS device at locations selected for NCAT water permeability testing and pavement coring. Air permeability testing was conducted immediately preceding water permeability testing to eliminate the potential for water infiltration into the air permeameter. Test locations were displaced approximately 6 inches longitudinally from pre-selected water permeability test locations to minimize the potential for the grease seal produced by the ROMUS device to contaminate the surface to be tested with the NCAT device.

2.2.5 Pavement Coring

Upon completion of air and water permeameter testing, cores were cut in the exact location of the water permeameter test. The six-inch diameter circular seal residue from the NCAT permeameter served as a guide for positioning the core drill. After the core was cut and removed from the pavement, it was marked and transported to the lab for bulk density testing using the Corelok device. If a core was damaged, a substitute test site was used to ensure a minimum of six test sites per layer.

2.3 Statistical Analysis of Field Studies

A formal analysis of variance (ANOVA) was conducted to measure sources of variation influencing density and water permeability. The F-test was used to determine statistical significance of each variable and reported in three ranges (<0.01; 0.01 to <0.05; and 0.05 to 0.10) to help understand the degrees of significance, rather than significance at an absolute level, such as 0.05. In some cases, it was not possible to test a variable due to lack of data, or a high degree of collinearity between variables that would have not made it possible to discern between significant variables. Main effects and two-way interactions were tested, and three-way interactions and higher were not tested to conserve degrees of freedom for significance testing (six test sites per project limits total pooled observations and significance sensitivity).

Tables 2.2 and 2.3 provide a summary of statistical significance tests of variables for field permeability and final pavement density, respectively. Because of significant differences in permeability between fine-graded and coarse-graded mixes, each was analyzed separately. For each gradation, all project data were pooled to test the variable of interest. Appendix A provides results of significance tests for individual projects. It must be noted that these findings are strictly limited to data collected in this study, and may not represent all mixes constructed using WisDOT design standards.

Permeameter test variability was relatively high for fine-graded mixes. Test variability of the NCAT permeameter, as a percentage of total individual project variability, ranged from 5% to 87% on fine-graded mixes, and from 3% to 13% on coarse-graded mixes. These measures indicate testing of coarse mixes is more repeatable than fine mixes.

Table 2.2 Statistical Significance Results for Field Permeability

Variable (1)	Permeability Fine Mix (2)	Permeability Coarse Mix (3)
Main Effects		
Base 2 levels (rigid, flexible)	***	*
Base 3 levels (PCC, HMA, CABC)	***	*
Source	***	no test
Density	***	*
Ndes	***	no test
NMAS	N/S	no test
Thickness	***	**
Thickness/NMAS Ratio	***	**
Aggregate Ratios		
1. Ratio, Passing No.4 CA/FA	*	- - -
2. Fine Aggregate Angularity	N/S	- - -
3. Ratio, (P1/2 - P3/8)/(P4 - P8)	***	- - -
4a. Bailey 1	N/S	- - -
4b. Bailey 2	N/S	- - -
4c. Bailey 3	**	- - -
Interactions - Significant Only		
Base x Source	**	no test
Base x Ndes	***	no test
Thickness x Base	***	no test
Thickness/NMAS x Base	***	N/S
Thickness x Source	***	no test
Thickness/NMAS x Source	***	no test
Thickness x Ndes	*	***
Thickness/NMAS x Ndes	**	***
Thickness/NMAS x Ratio 1	*	- - -
Thickness/NMAS x Ratio 3	***	- - -
Thickness/NMAS x Ratio 4c	**	- - -
Density x Base	***	*
Density x Source	***	no test
Density x Thickness	*	**
Density x Thickness/NMAS	**	**
Density x Ndes	***	***
Density x Ratio 1	**	- - -
Density x Ratio 2	***	- - -
Density x Ratio 4a	***	- - -

Density x Ratio 4b	***	- - -
Density x Ratio 4c	***	- - -

Significance Levels: N/S = Not Significant; * = 0.05 < p-value < 0.10;** = 0.01 < p-value< 0.05; *** = p-value < 0.01
no test = variable had collinearity with other variable(s);   - - - = variable not tested

Table 2.3 Statistical Significance Results for Field Density

Variable (1)	Final Density Fine Mix (2)	Final Density Coarse Mix (3)
Main Effects		
Base 2 levels (rigid, flexible)	N/S	***
Base 3 levels (PCC, HMA, CABC)	- - -	- - -
Source	***	***
Ndes	***	no test
NMAS	***	no test
Thickness	**	N/S
Thickness/NMAS Ratio	N/S	N/S
Passing 4.75mm	***	no test
Passing 75um	***	no test
Lab Voids	***	no test
VMA	***	no test
VFA	N/S	no test
AC%	**	no test
Interactions – Base, Thickness, t/NMAS only		
Base x Source	no test	no test
Base x Ndes	no test	no test
Thickness x Base	***	***
Thickness/NMAS x Base	***	N/S
Thickness x Source	N/S	***
Thickness/NMAS x Source	N/S	N/S
Thickness x Ndes	**	no test
Thickness/NMAS x Ndes	***	no test
Thickness x P475mm	***	no test
Thickness/NMAS x P475mm	***	no test
Thickness x P75um	N/S	no test
Thickness/NMAS x P75um	N/S	no test
Thickness x Voids	*	no test
Thickness/NMAS x Voids	no test	no test
Thickness x VMA	N/S	no test
Thickness/NMAS x VMA	no test	no test
Thickness x VFA	**	no test
Thickness/NMAS x VFA	no test	no test
Thickness x AC%	N/S	no test
Thickness/NMAS x AC%	N/S	no test

Significance Levels: N/S = Not Significant; * = 0.05 < p-value < 0.10;** = 0.01 < p-value< 0.05; *** = p-value < 0.01
no test = variable had collinearity with other variable(s);   - - - = variable not tested

The following sections are graphical presentations and interpretations for fine-graded and coarse-graded mixes, respectively, to support findings from the statistical analysis.

2.3.1 Fine Mixes

A. Base. Two tests were conducted for base type: a 2-level test for rigid and flexible, and a 3-level test for PCC, HMA, and CABC. In both cases, base and Ndes had an effect on permeability. Figure 2.1 provides the relationship between permeability and the three base types. Source and Ndes data were broken down to show their relationship with base. The 'Base*Ndes' interaction was significant, and this is readily shown with higher permeability Ndes=100 data points on rigid bases. This infers that high Ndes mixes may be more difficult to compact on rigid bases, thus causing a more permeable pavement.

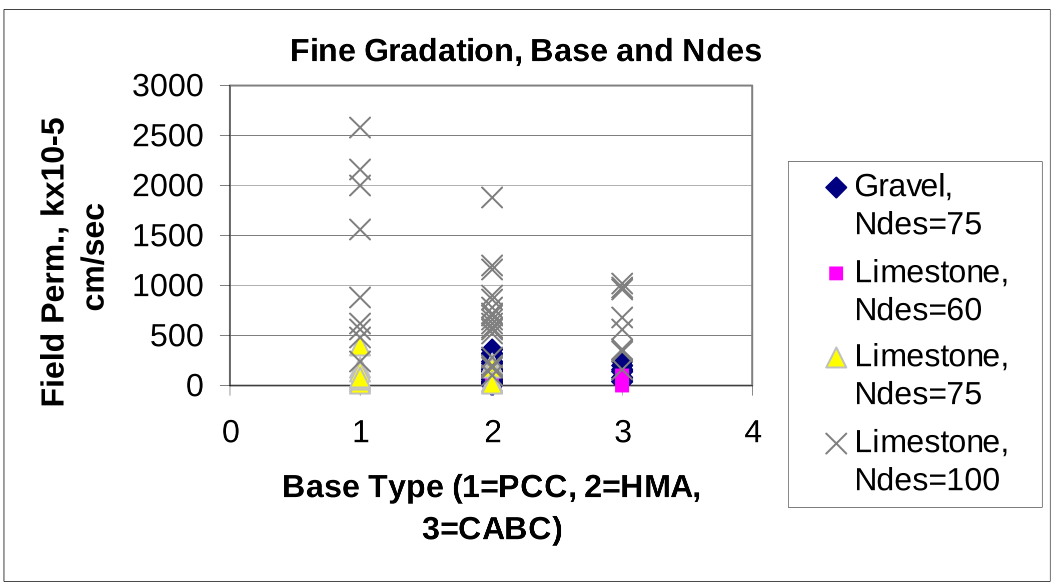


Figure 2.1 Field Permeability and Base Type (Fine Mixes)

B. Source. Limestone, when compared to gravel, had a greater influence on changes in permeability, as shown in Figure 2.2. When compared across a similar density range, say 90% to 95%, limestone-source pavements were more permeable. Several two-way interactions also measured the influence that aggregate source had on permeability. The 'Density x Source' interaction suggests that limestone was more difficult to compact, thus producing lower density and higher permeability. Likewise, the 'Thickness x Source' interaction and 'Base x Source' interaction also indicated that limestone was more sensitive to thickness and base type when trying to achieve density, thus creating a response in permeability.

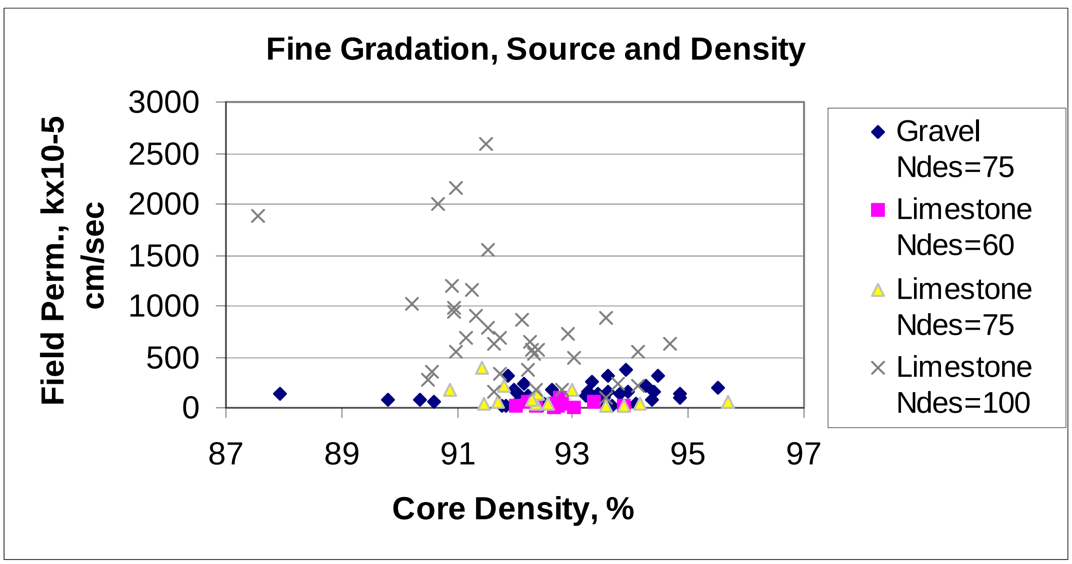


Figure 2.2 Field Permeability and Source (Fine Mixes)

C. Density. Lower density pavements were more permeable for limestone-source mixes, while no trend was observed for gravel-source mixes, as illustrated in

Figure 2.2. The ability to achieve final density for fine-graded mixes was influences by source, Ndes, NMAS, thickness, passing 4.75mm and 75um sieves, lab voids, VMA, and %AC. The layer t/NNMAS ratio was not statistically significant, while the interactions of layer thickness with base, Ndes, passing 4.75mm sieve, and voids were all found to be statistically significant.

D. Ndes. Higher Ndes mixes were more permeable, as shown in Figure 2.3. The 'Density x Ndes' interaction also indicates that higher Ndes mixes were more difficult to compact, producing a higher permeability rate. To further support this, statistical results confirm Ndes had a significant affect on achieving final density.

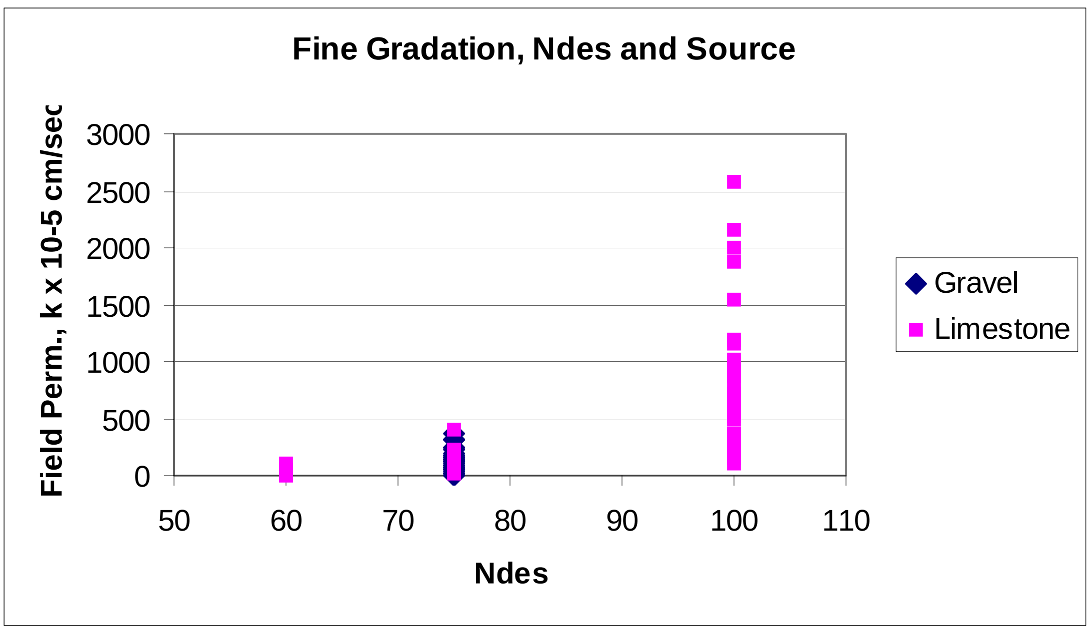


Figure 2.3 Field Permeability and Ndes (Fine Mixes)

E. Thickness. For limestone-source mixes, layer thickness in the range of 2 to 3 inches was more permeable (see Figure 2.4). Gravel-source mixes had little effect across all thickness ranges. Research findings in the report found that lab permeability of field cores was higher for thin layers, and lower for thick layers. The difference between field and lab tests may be the confinement provided at the bottom of the field layer.

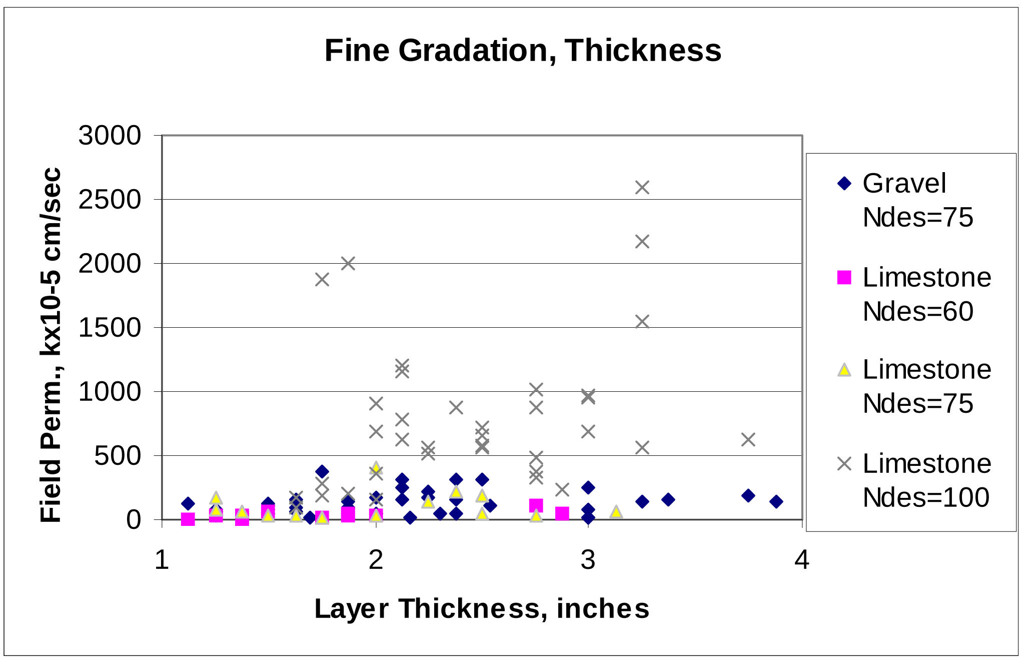


Figure 2.4 Field Permeability Thickness (Fine Mixes)

Figure 2.5 illustrates the relationship between thickness and density for both sources, where Ndes=100 limestone mixes had lower final density than gravel mixes and lower Ndes limestone mixes across a range of layer thickness. A slight trend can be observed between thickness and density where thinner layers had a lower density, and thicker layers had a higher density.

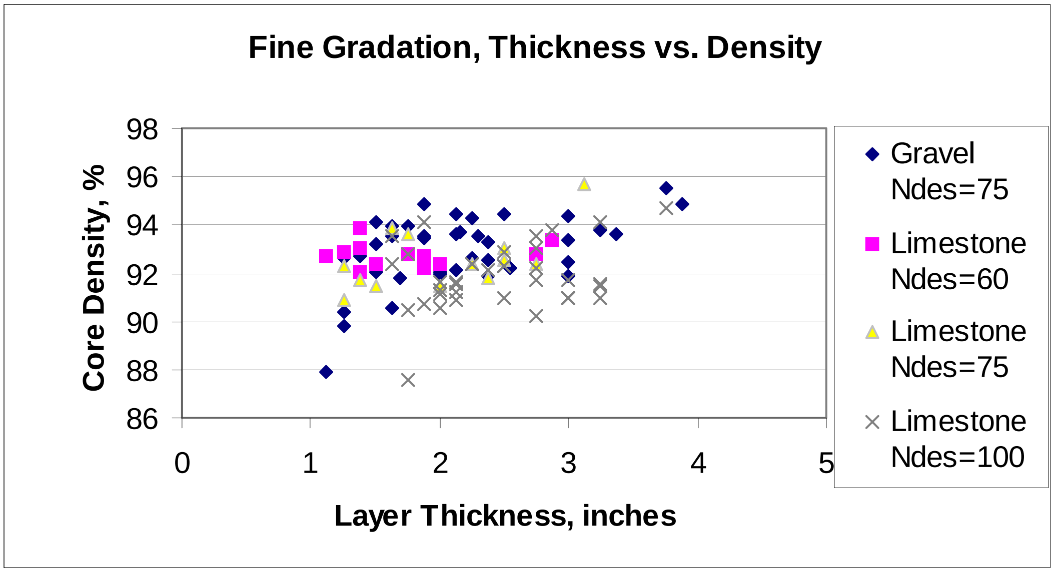


Figure 2.5 Layer Thickness and Mat Density (Fine Mixes)

F. Thickness/NMAS Ratio. Higher t/NMAS ratios produce increased permeability for limestone mixes with Ndes = 100 (See Figure 2.6). No trends were observed for the other limestone mixes (Ndes = 60, 75), nor for the gravel mixes. T/NMAS ratios below 2 for both sources produced lower final density. In addition, lower density values for limestone mixes were observed below a t/NMAS ratio of 3, as shown in Figure 2.7. These results suggest that ratios less than 2 have the ability to impact final pavement density.

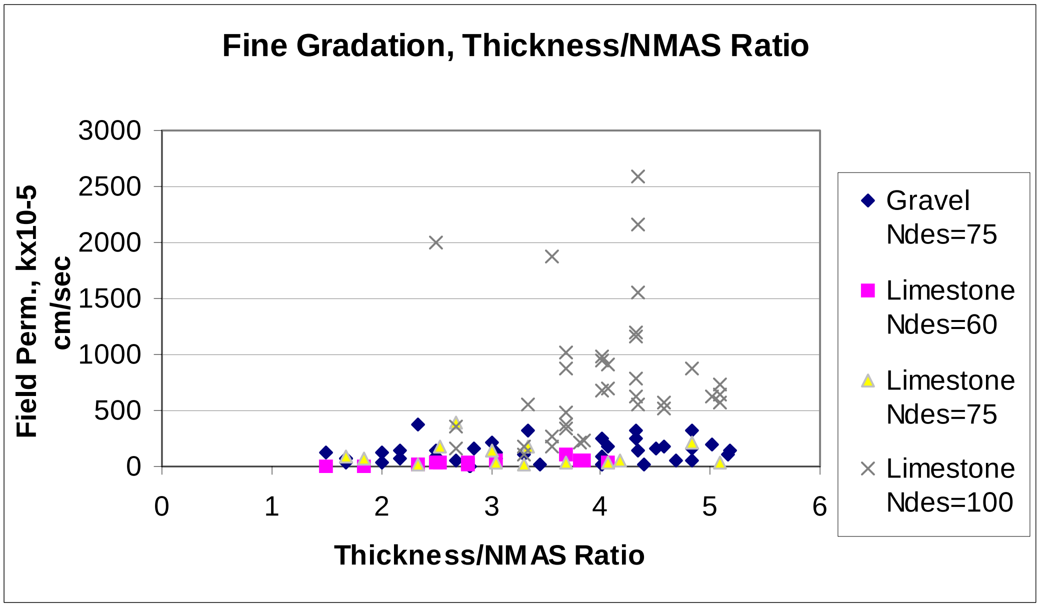


Figure 2.6 Field Permeability and Layer Thickness/NMAS Ratio (Fine Mixes)

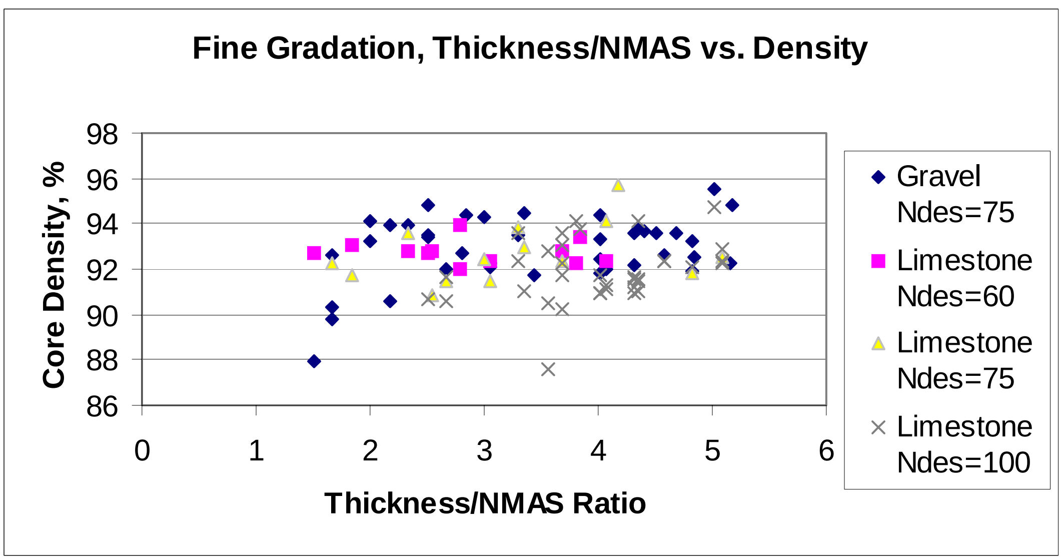


Figure 2.7 Layer Thickness/NMAS Ratio and Mat Density (Fine Mixes)

G. <u>NMAS</u>. Figure 2.8 shows scatter among 12.5-mm and 19-mm NMAS mixes, and no trend or difference in mean level was observed. The statistical analysis and this figure are in disagreement with the NCHRP 9-27 study, and other studies in Florida, Virginia, and Maine, that found NMAS to be a significant factor affecting permeability (Cooley et. al 2001).

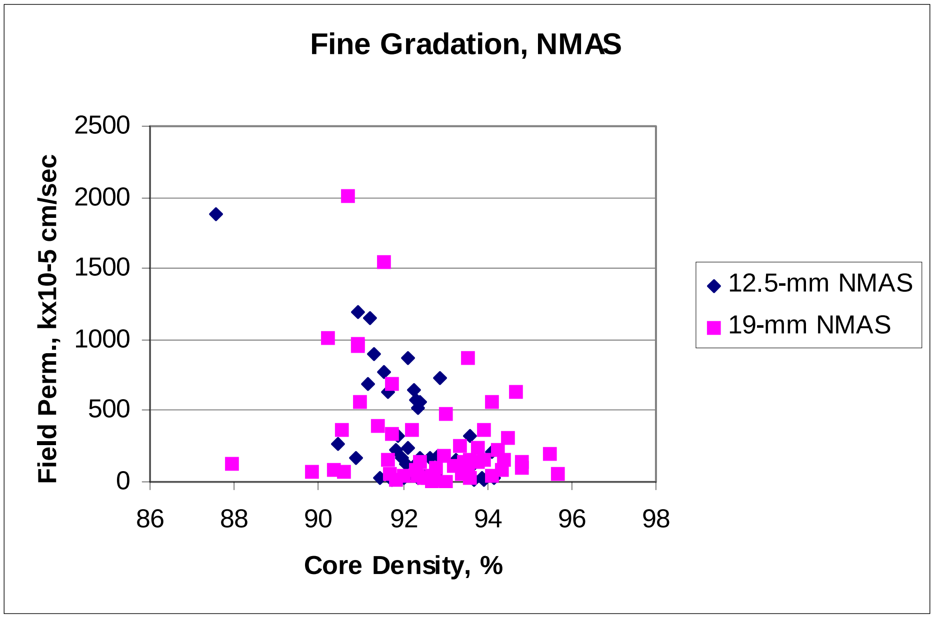


Figure 2.8 Field Permeability and NMAS (Fine Mixes)

H. Aggregate Ratios. Four aggregate ratios were evaluated.

(1) Ratio of Percentage Passing the No. 4 sieve (P4 Ratio) contributed by coarse aggregates and sand. For this report, the P4 Ratio is defined as the P4 fraction contributed by the sands divided by the P4 contributed by the coarse aggregate. For example, an aggregate blend containing 40% coarse aggregate (P4=17%) and 60% sand (P4=95%) would have a total P4=63.8%. Of these P4 materials, 10.6% were contributed by the coarse aggregate and 89.4% from the sands, yielding a P4 Ratio of 8.4. Statistical analysis found moderate significance in mean levels among ratios; however, the plot in Figure 2.9 shows no specific trend.

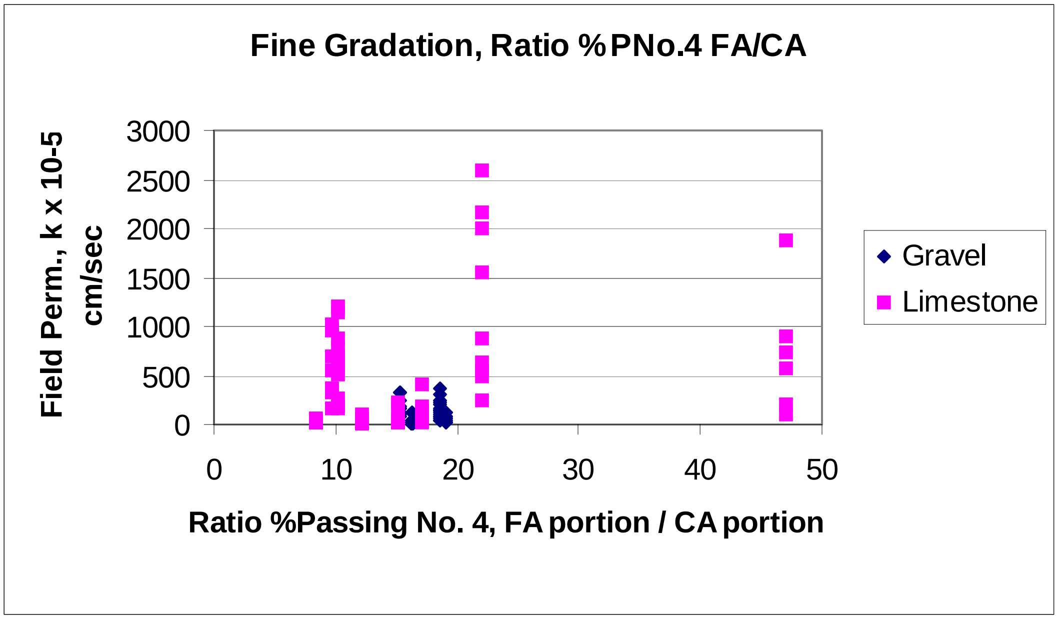


Figure 2.9 Field Permeability and Ratio of Percentage Passing No. 4 Sieve, Fine Aggregate Portion / Coarse Aggregate Portion (Fine Mixes)

(2) Fine Aggregate Angularity. FAA did not have an effect on permeability. FAA test results among projects ranged from 41.4 to 46.8.

(3) Ratio of (%P1/2 - %P3/8) / (%PNo.4-%PNo.8). Figure 2.10 shows a relationship for Limestone, but no trend for Gravel. For a fine crushed-limestone mix, the relative contribution of a narrower gap between Percent Passing ½" sieve (%P1/2") and Percent Passing 3/8" sieve (%P3/8"), or wider gap between Percent Passing No. 4 sieve (%P4) and Percent Passing No. 8 sieve (%P8), produced a more permeable mat. Figures 2.11 and 2.12 illustrate higher permeability as the gaps increase between coarse aggregates (%P1/2" and %P3/8") and fine aggregates (%P4 and %P8),

respectively. This suggests relative differences in these sieves may have an effect on internal void structure, and measured permeability, of the compacted material.

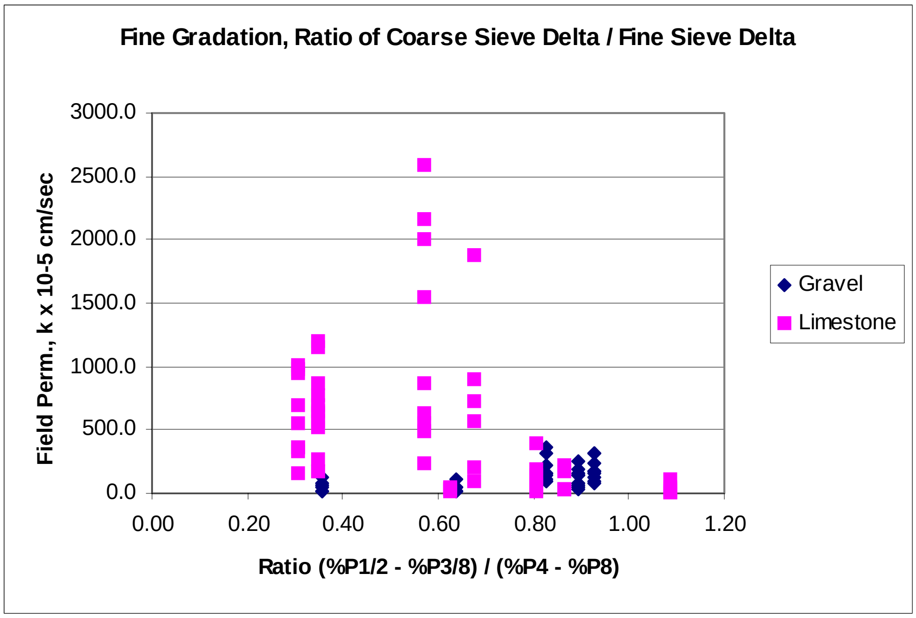


Figure 2.10 Field Permeability and Ratio of Coarse Sieve Difference (%P1/2” – %P3/8”) and Fine Sieve Difference (%P No.4 – %P No.8)

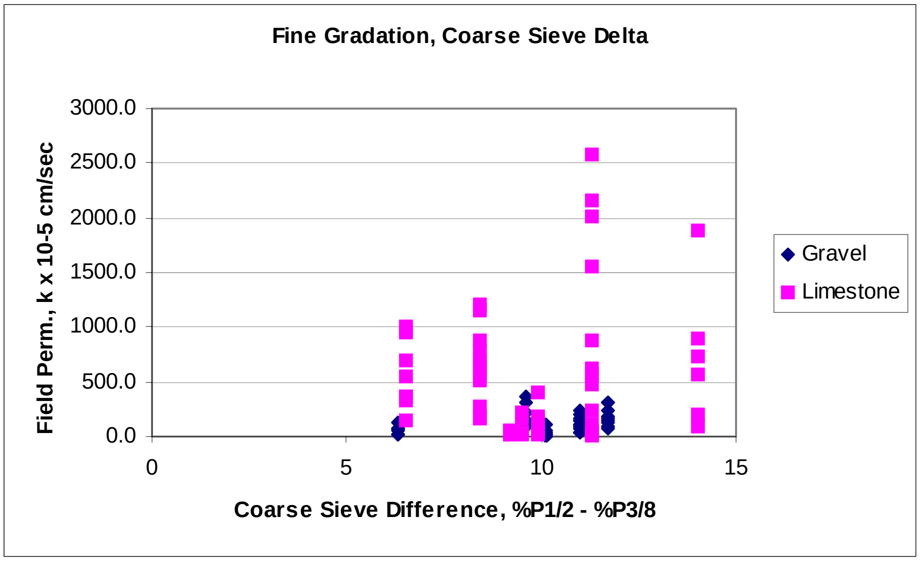


Figure 2.11 Field Permeability and Coarse Sieve Difference (%P1/2” – %P3/8”)

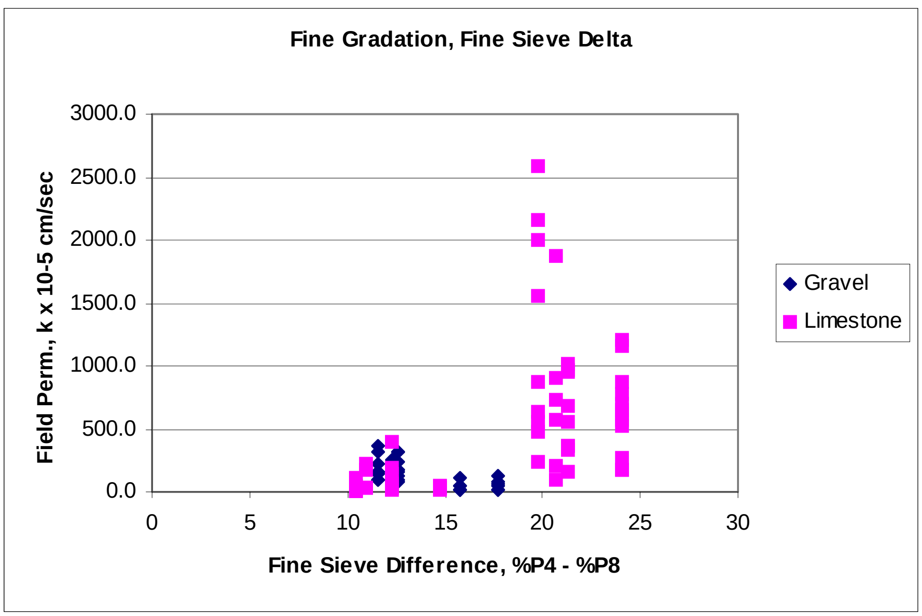


Figure 2.12 Field Permeability and Fine Sieve Difference (%P4 – %P8)

(4) Bailey Method. The Bailey Method provides a rational design method for measuring and understanding the packing of aggregates (Vavrik et. al 2002). Three ratios were tested: (1) Coarse Aggregate Ratio, (2) Fine Aggregate Coarse Portion Ratio, and (3) Fine Aggregate Fine Portion Ratio (FA_F). Only the latter ratio was found to be significant in explaining changes in permeability. Computation for (FA_F) are as follows:

19.0-mm NMAS mixes: FA_F = %PNo.50 / %PNo.16.

12.5-mm NMAS mixes: FA_F =.%PNo.100 / %PNo.30.

From a practical perspective, a larger relative percentage of material passing the finer sieves (No.16 or No. 30) reduces mix permeability (see Figure 2.13). However, there is a bell-shaped appearance in Figure 2.13 with all data and no solid trend. When the gravel data were removed, there was a trend for limestone, but there were low limestone ratios of 0.19 (USH-10 12.5-mm, Ndes=60 mix on CABC) and 0.26 (Wisconsin Avenue 12.5-mm, Ndes=75 mix on PCC).

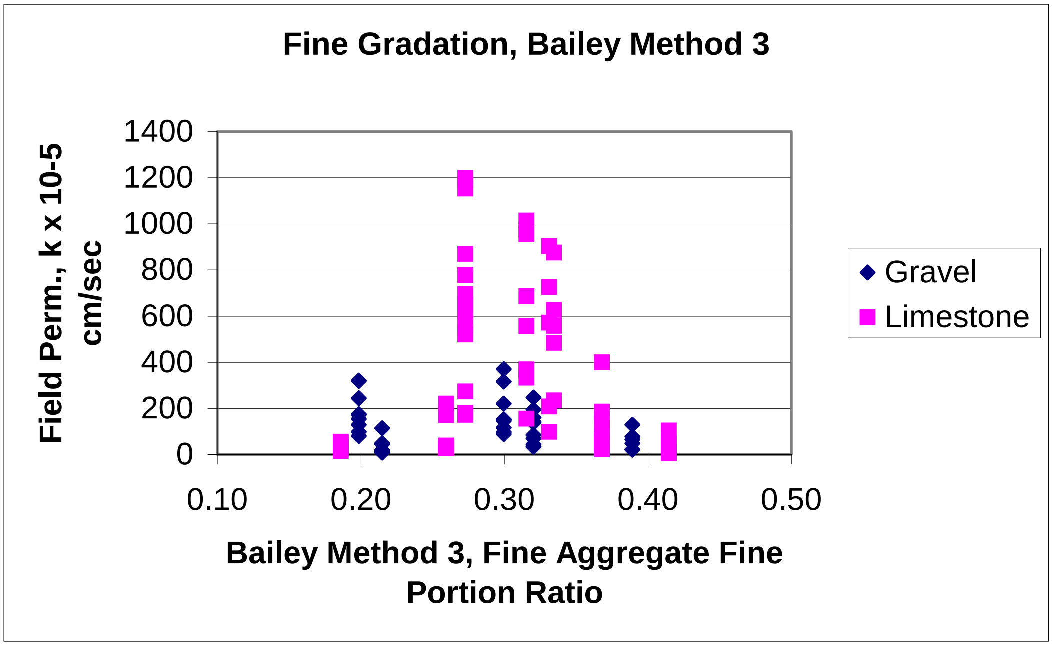


Figure 2.13 Field Permeability and Bailey Method 3 (Fine Mixes)

I. Passing No. 8 Sieve. Analysis of aggregate ratios found that coarse sieve and fine sieve differences have an effect on permeability. Figure 2.14 illustrates the relationship between three Passing No. 8 Sieve ranges (< 40%, 40-45%, and >45%) against density and permeability. For similar density ranges, say 90% to 95%, the more coarse mixes (< 40% and 40-45%) were more permeable. This finding is in agreement with the literature. Laboratory testing and analysis in the later section of this report further addresses this issue.

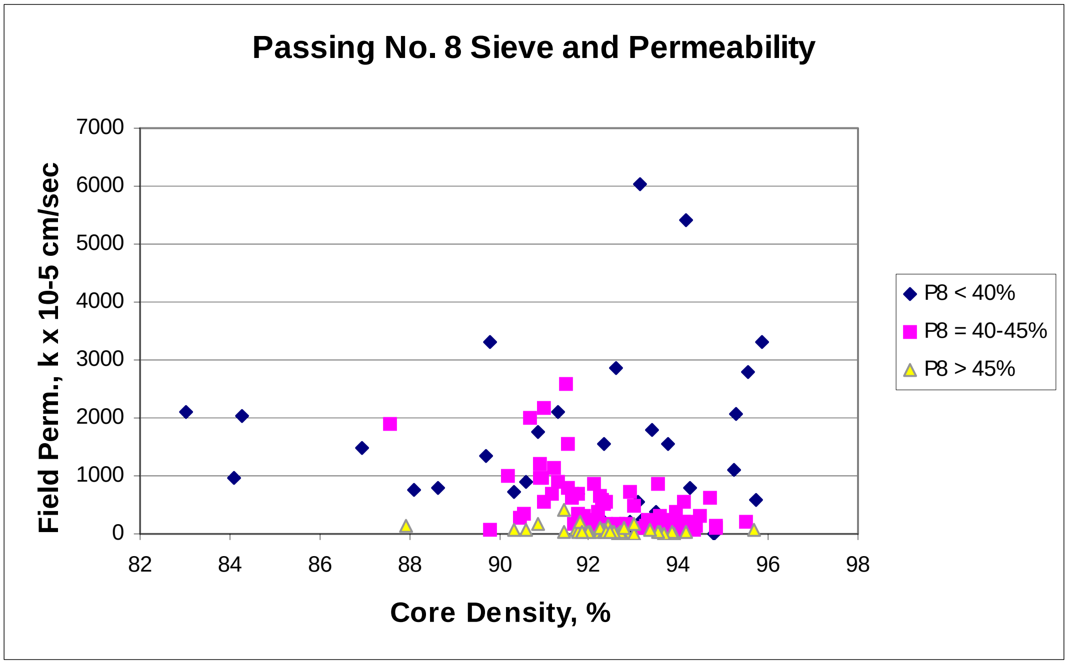


Figure 2.14 Field Permeability and Passing No. 8 Sieve

2.3.2 Coarse Mixes

The following are an interpretation of results for coarse mixes only. Due to a limited data set and confounding of variables, several variables and their interactions could not be tested for significance.

A. Base. Similar to fine mixes, two tests were conducted for base type: 2 levels (rigid and flexible) and 3 levels (PCC, HMA, and CABC). In both tests, base had a moderate impact on permeability. Figure 2.15 provides the relationship between permeability and two base types, PCC and CABC. The STH-17 gravel-source project constructed on CABC helped to produce a higher mean permeability level.

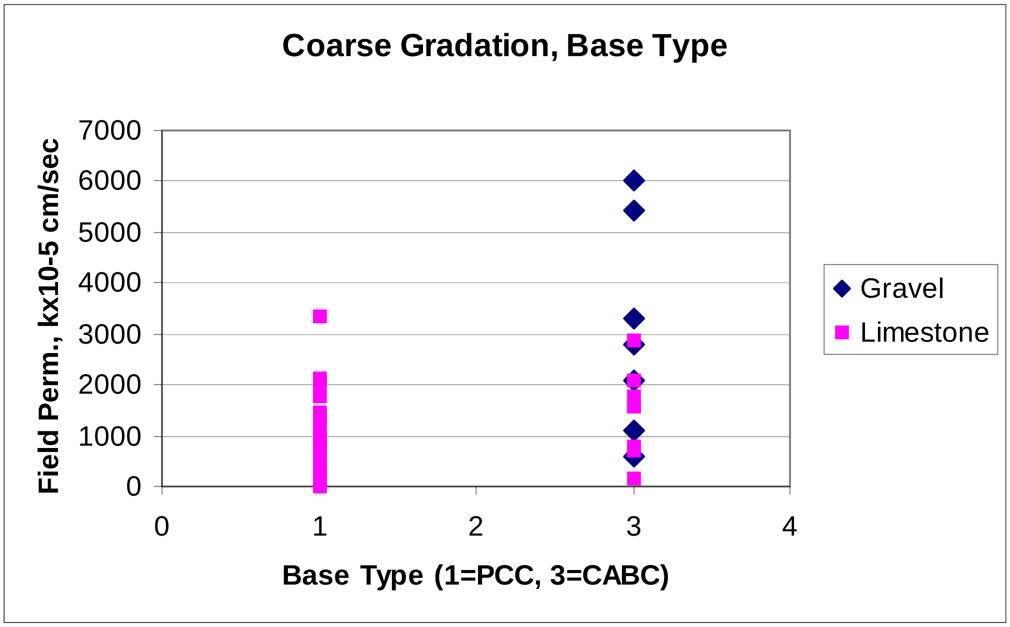


Figure 2.15 Field Permeability and Base Type (Coarse Mixes)

B. <u>Density</u>. For coarse mixes, there was moderate evidence that density affected permeability, however, Figure 2.16 illustrates that this may be from higher permeability on the more dense, gravel-source, STH-17 project. This figure also shows no discernible trend between density and permeability for coarse mixes.

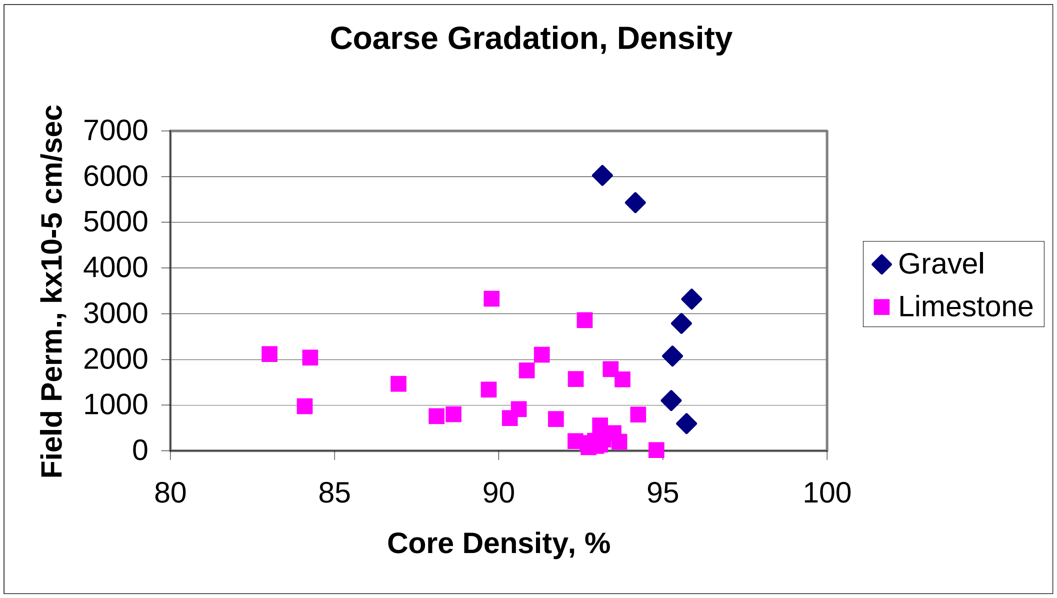


Figure 2.16 Field Permeability and Density (Coarse Mixes)

C. Thickness. The plot in Figure 2.17 suggests that thicker layers are more permeable, however, the moderate statistical significance of this variable was attributed to the large scatter in the gravel-source data in the vicinity of 4 inches. Figure 2.18 provides an important interactive relationship between density, permeability, and thickness where density was more difficult to achieve on thinner mats. Thus, thickness had an effect on achieving coarse-mix density, but density had no effect on permeability.

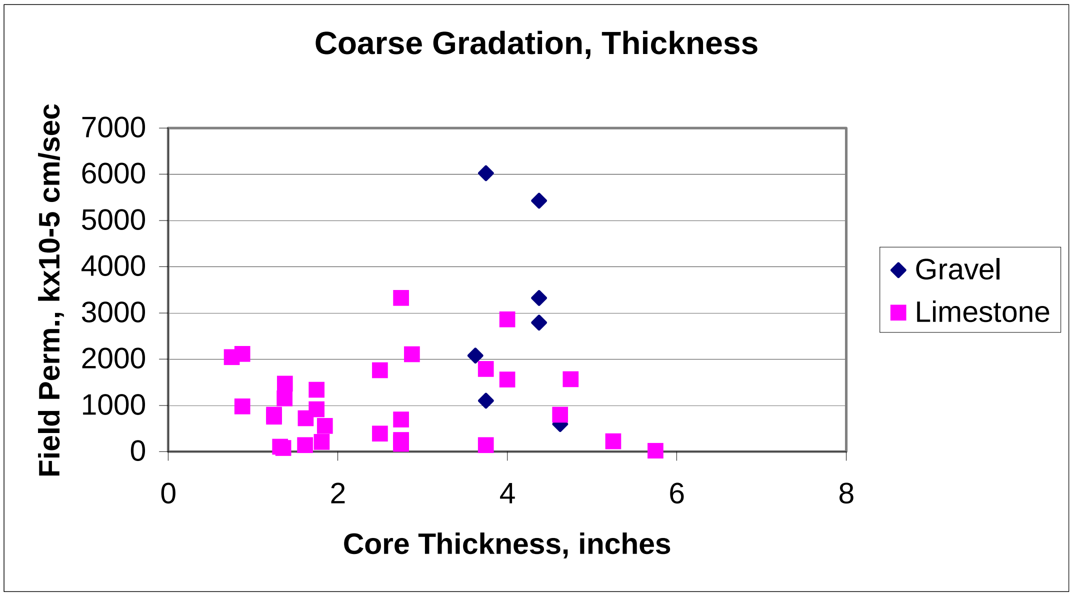


Figure 2.17 Field Permeability Thickness (Coarse Mixes)

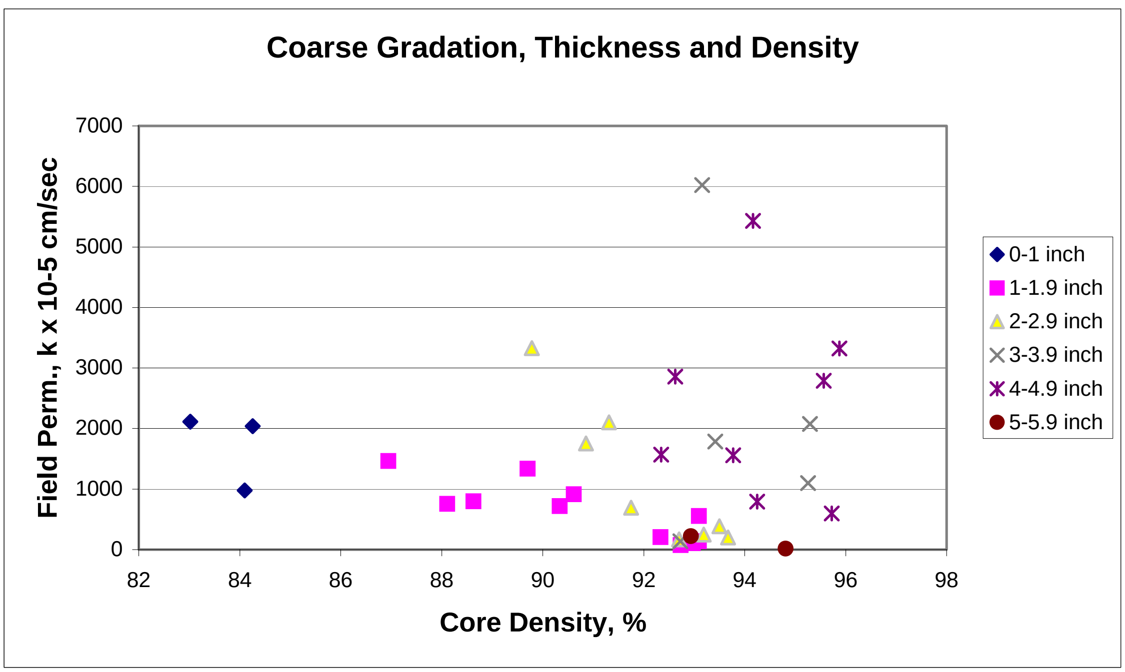


Figure 2.18 Field Permeability, Thickness and Density (Coarse Mixes)

D. Thickness/NMAS Ratio. Smaller ratios for limestone-source mixes appeared more permeable than higher ratios, as shown in Figure 2.19. No trend was observed with the gravel-source mix. Figure 2.20 illustrates an interactive relationship between t/NMAS ration, density, and permeability, where density was more difficult to achieve with smaller t/NMAS ratios. Therefore, the t/NMAS ratio had an effect on achieving coarse-mix density, however, density had no effect on permeability. In general, t/NMAS ratios above 4 produced a density above 92%.

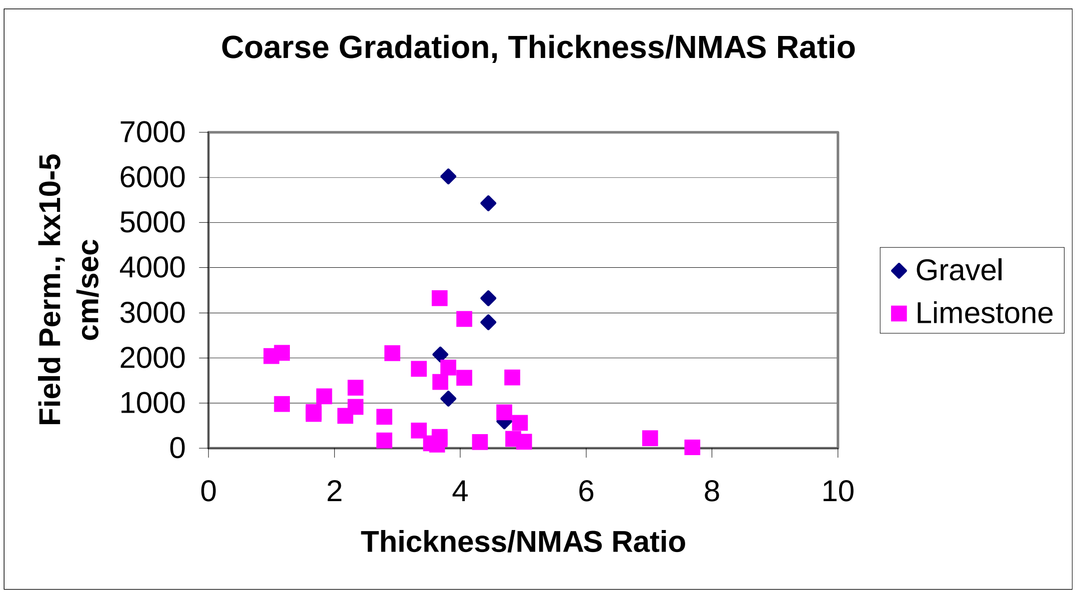


Figure 2.19 Field Permeability Thickness/NMAS Ratio (Coarse Mixes)

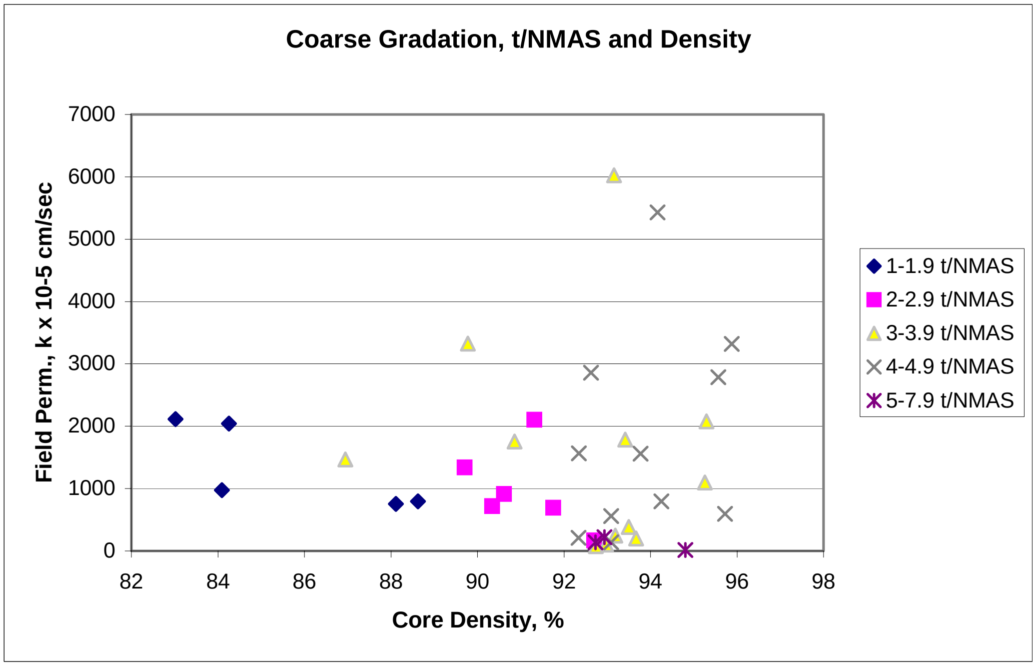


Figure 2.20 Field Permeability, Thickness/NMAS Ratio and Density (Coarse Mixes)

2.3.3 Density Growth

Analysis of variance was conducted for density growth on individual projects with results shown in Tables 2.4 and 2.5. Number of passes were adjusted in the analysis to compare results of initial density gain with the breakdown roller with density growth across all rollers. First, all passes were used (Table 2.4); then only the first 4 passes were used to assess initial gain in the density (Table 2.5).

Project data were not pooled since different equipment and materials were used among projects, and pooled results would have been difficult to interpret and generalize across similar variables. For example, a thin pavement compacted with low lab air voids may be easy to compact primarily because of the low lab air voids, however, a statistical significance test may possibly yield the thin layer as the significant variable. Thus, the analysis "blocked" and removed project variables such as mix type, %AC, % dust, lab air voids, VMA, roller weight, roller width, and numerous other project factors. By removing those variables, the analysis was then able to focus on key independent variables of interest though to affect density growth, namely, layer thickness, number of passes, mat temperature, and their interactions.

Table 2.4 Statistical Significance Results for Density Growth (All Passes)

Variable (1)	I-43 19-mm Coarse (2)	STH-23 19-mm Fine (3)	STH-23 12.5-mm Fine (4)	Wis Ave 19-mm Fine (5)	Wis Ave 12.5-mm Fine (6)	USH 10 19-mm Fine (7)	I-894 19-mm Fine (8)	I-894 12.5-mm Fine (9)	STH-21 19-mm, Fine (10)	STH-21 12.5-mm, Fine (11)	USH-8 19mm(1) Fine (12)	USH-8 19mm(2) Fine (13)	USH-8 12.5-mm Fine (14)	I-94 25-mm Coarse (15)	STH-17 25-mm Coarse (16)
Degrees of Freedom	127	100	87	113	59	58	108	81	96	233	132	157	71	106	92
Thick	N/S	**	***	N/S	N/S	***	N/S	N/S	***	***	***	N/S	N/S	***	***
Temp	---	***	***	***	***	***	***	***	***	***	***	***	***	***	***
Thick*Temp	---	*	N/S	**	N/S	N/S	N/S	***	N/S	***	N/S	**	**	N/S	***
Passes	***	N/S	N/S	***	***	***	***	***	***	***	***	**	***	***	N/S
Thick*Pass	N/S	N/S	N/S	**	N/S	N/S	N/S	N/S	*	N/S	N/S	N/S	***	N/S	N/S
Temp*Pass	---	***	***	***	***	***	***	***	N/S	***	***	***	***	***	***
Thick*Temp*Pass	---	N/S	***	**	N/S	N/S	N/S	**	N/S	***	**	N/S	N/S	N/S	N/S
Density Testing,%	48	22	15	32	22	10	9	13	32	18	16	29	10	16	21

Significance Levels: N/S = Not Significant; * = 0.05 < p-value < 0.10;** = 0.01 < p-value< 0.05;
*** = p-value < 0.01

Table 2.5 Statistical Significance Results for Density Growth (First 4 Passes)

Variable (1)	I-43 19-mm Coarse (2)	STH-23 19-mm Fine (3)	STH-23 12.5-mm Fine (4)	Wis Ave 19-mm Fine (5)	Wis Ave 12.5-mm Fine (6)	USH 10 19-mm Fine (7)	I-894 19-mm Fine (8)	I-894 12.5-mm Fine (9)	STH-21 19-mm, Fine (10)	STH-21 12.5-mm, Fine (11)	USH-8 19mm(1) Fine (12)	USH-8 19mm(2) Fine (13)	USH-8 12.5-mm Fine (14)	I-94 25-mm Coarse (15)	STH-17 25-mm Coarse (16)
Degrees of Freedom	38	45	43	72	36	49	55	31	35	100	89	53	17	26	22
Thick	N/S	**	***	N/S	N/S	***	***	***	***	N/S	***	N/S	N/S	N/S	***
Temp	---	***	***	***	***	***	***	***	***	***	***	***	***	***	***
Thick*Temp	---	***	***	***	N/S	*	N/S	N/S	N/S	***	N/S	**	*	**	***
Passes	***	***	***	***	***	N/S	***	***	***	***	***	***	***	***	***
Thick*Pass	**	**	***	**	***	*	**	N/S	N/S	***	N/S	*	N/S	*	*
Temp*Pass	---	N/S	***	N/S	***	***	***	***	***	***	***	***	N/S	***	N/S
Thick*Temp*Pass	---	N/S	*	***	*	N/S	N/S	N/S	**	***	N/S	N/S	N/S	N/S	***
Density Testing, %	9	8	6	20	16	10	11	7	8	19	8	22	4	17	4

Significance Levels: N/S = Not Significant; * = 0.05 < p-value < 0.10;** = 0.01 < p-value< 0.05;
*** = p-value < 0.01

In Table 2.4 (all passes), it was determined that mat temperature was found to be significant across projects and different NMAS layers. Number of passes was significant on all limestone-source projects, while 2 of 3 gravel-source projects did not find passes to be significant. This is supported by Figure 2.5 where fine gravel-source projects had a slightly higher final density than fine limestone-source projects. The interaction of passes with the declining mat temperature was significant on all projects, except the STH-21 19-mm mix.

During field data collection, it was observed that a greater density gain was achieved during the initial passes with the breakdown roller, then decreasing mix temperature and void spaces increased the resistance of the mat to densification. In Table 2.5, the data set was reduced to the first 4 passes to analyze densification with the breakdown roller. Mat temperature was again found to be a significant factor in density growth. The interactions of thickness and passes, and thickness and temperature were also influential on a majority of project layers. Similar to the full-pass analysis, thickness was not a significant factor in density growth across all projects during initial breakdown compaction.

Plots of the changes in density mean levels with varying thickness for I-894 are provided in Figures 2.21 and 2.22. These growth trends are typical of all projects where there was a relatively large density increase from initial passes, then a tapering effect with remaining passes. Final growth was as a function of passes, and the effect of thickness was random. Additional project density-growth plots are provided in Appendix B. Due to various field constraints, it was not possible to collect data on each project layer in the study.

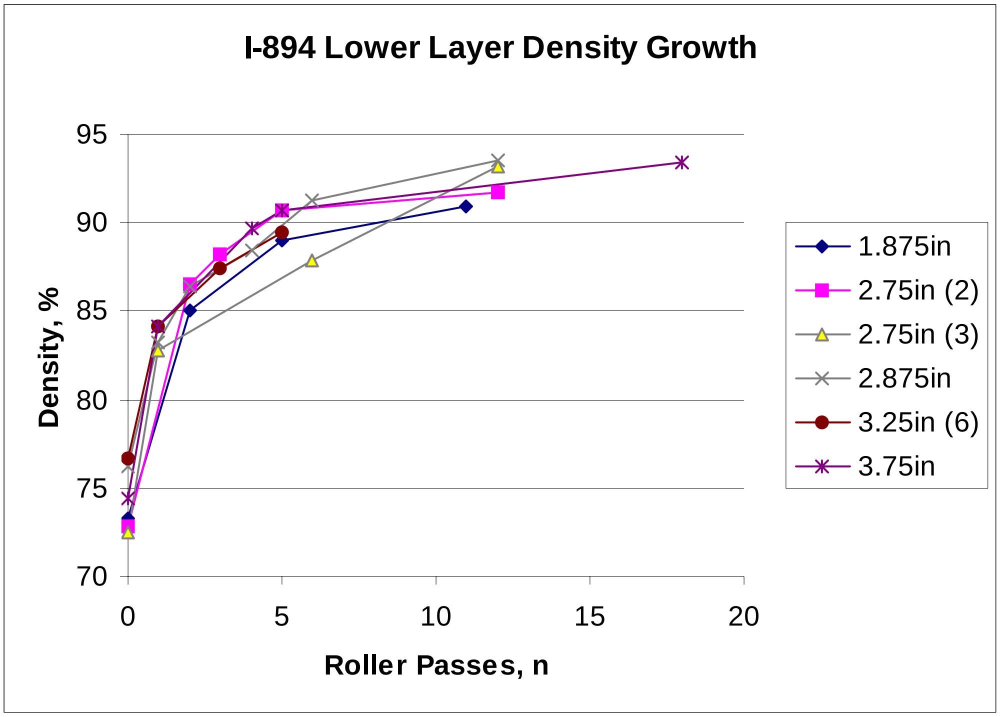


Figure 2.21 Density Growth on I-894 19-mm Lower Layer Mix

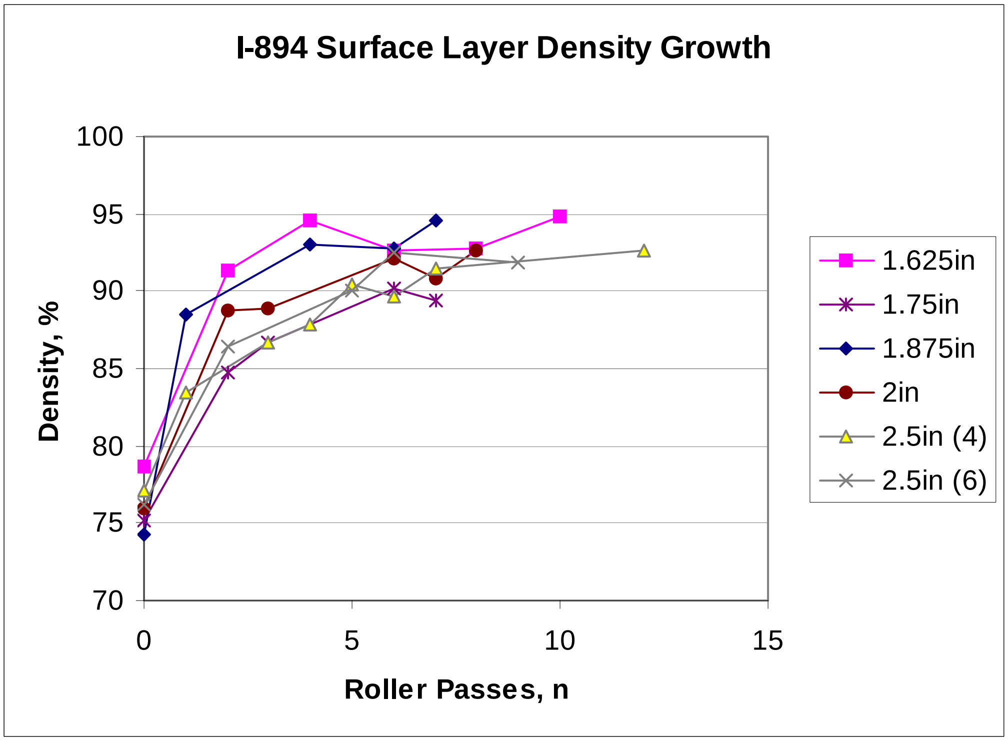


Figure 2.22 Density Growth on I-894 12.5-mm Surface Layer Mix

Based on the statistical analysis, and representative plots from the I-894 project, density growth was primarily influenced by mat temperature and number of passes. Layer thickness was a factor on a project-specific basis.

2.4 Investigation of Specification Criteria

Density is one of the most important factors of a durable, long-lasting pavement. This study found that lower density, limestone source, fine-graded Ndes=100 mixes were more permeable, while no trend was observed for gravel-source mixes. NCAT has recommended the following permeability criteria for coarse-graded mixes only, as shown in Table 2.6. To date, no other coarse-graded recommended criteria have been published, nor have any criteria been published for fine-graded mixes. These criteria are based upon the NMAS of the mix, and critical values should likely be different for fine- and coarse-graded mixes even though the NCAT study involved only coarse-grades mixes (Cooley et. al 2001).

Table 2.6 NCAT Recommended Permeability Criteria for Coarse-Graded Mixes (Adopted from [1])

NMAS, mm (1)	K x 10^{-5} cm/sec, maximum (2)	$\%G_{mm}$, minimum (3)
9.5	100	92.3
12.5	100	92.3
19	120	94.5
25	150	95.6

As stated earlier, NCAT and other studies have determined NMAS has a significant effect on permeability, while this study has not found NMAS to be a significant factor. Thus, applying NMAS-specific criteria would not be justified. However, for sake of investigation, an analysis was conducted to determine if NCAT criteria are achievable. Table 2.7 provides both a frequency and percentage of all fine-graded test sites that met, or failed to meet, these permeability and density thresholds. Field permeability was measured using the NCAT permeameter, and density was measured using field cores. For nearly all criteria combinations, a greater percentage of failure occurred.

Table 2.7 Pass/Fail Results for Fine-Mix WisDOT Projects applied to NCAT Recommended Permeability Criteria

Criteria (1)	K x 10^{-5} cm/sec (2)	%Gmm (3)
(a) 12.5-mm NMAS		

Pass	18	40%	23	51%
Fail	27	60%	22	49%
Total	45	100%	45	100%
(b) 19-mm NMAS				
Pass	23	41%	5	9%
Fail	33	59%	51	91%
Total	56	100%	56	100%

The preferred method to establish a minimum density and maximum permeability value for various mix classifications is with actual performance data. This study can provide recommendations for the level of density needed to control permeability, however, the level of permeability to achieve a durable, long-lasting pavement is not known (for example, should the minimum level be k = 100x10^{-5} cm/sec, k = 300x10^{-5} cm/sec, or some other value). Both short-term and long-term monitoring of pavement performance is necessary to establish true levels.

Until a performance-based approach is adopted, a beginning approach would be to find the median value that produces a 50-50 pass-fail percentage. Table 2.8 provides cross-classified permeability values for all data, by source, and by Ndes. Best-fit regression equations to determine required density are also provided.

Table 2.8 Median "k" Values and Density for Fine-Mix Projects

Level (1)	Number of Samples (2)	k x 10^{-5} cm/sec (3)	Regression Equation (4)	R^2 (5)	Density Required, % (6)
(a) All Data					
- - -	101	152	Perm. = 10185 - 106.9xDensity	17.1	93.8
(b) Source					
Limestone	62	220	Perm. = 17525 - 185.5xDensity	31.1	93.3
Gravel	39	114	Regression Equation Not Significant	---	---

(c) Ndes					
60	12	28	Regression Equation Not Significant	---	---
75	53	97	Regression Equation Not Significant	---	---
100	36	627	Perm. = 18167 - 190.0xDensity	32.6	92.3

One aggregate ratio has the potential to control permeability of fine-grades mixes: (%P1/2 - %P3/8) / (%PNo.4-%PNo.8). This ratio will be referred to as the "Coarse Sieve Delta / Fine Sieve Delta Ratio". Higher ratios have the potential to reduce permeability. Higher permeability results as the gaps increase between coarse aggregates (%P1/2" and %P3/8") and fine aggregates (%P4 and %P8), respectively. This suggests relative differences in these sieves may have an effect on internal void structure, and measured permeability, of the compacted material. The mix design would be adjusted to a sufficient ratio to withstand permeability by either increasing the difference between the coarse sieves, reducing the difference between the fine sieves, or both.

Table 2.9 provides sample data and calculations for this ratio. In the first example using data from I-894 (12.5-mm, E-30, limestone-source mix) specifies k=152 x10^{-5} cm/sec for all fine mixes, k=220 x10^{-5} cm/sec for limestone source, and k=627 x10^{-5} cm/sec for E-30, Ndes=100 mixes. Based on the fine mix permeability threshold (k=152 x10^{-5} cm/sec), a ratio exceeding 1.00 is desired. For the source permeability threshold (k=220 x10^{-5} cm/sec), a ratio of 0.8 is needed. Finally, for the Ndes classification (k=627 x10^{-5} cm/sec), a ratio of 0.8 should ensure this criteria is met.

In the second example using data from STH-23 (19-mm, E-3, gravel-source mix), gravel sources are more robust to the ratio. This mix would specify k=152 x10^{-5} cm/sec for all fine mixes, k=114 x10^{-5} cm/sec for gravel source, and k=97 x10^{-5} cm/sec for E-3, Ndes=75 mixes.

Table 2.9 Mix Design Calculations for Coarse Sieve Delta / Fine Sieve Delta Ratio

Mix Design (1)	% Passing ½" (2)	% Passing 3/8" (3)	% Passing No.4 (4)	% Passing No.8 (5)
I-894, 12.5-mm	98.4	84.4	62	41.3
	Coarse Delta = 14.0		Fine Delta = 20.7	
	Coarse Delta / Fine Delta = 14.0/20.7 = 0.68			
STH-23, 19-mm	90.3	84	68.9	51.2
	Coarse Delta = 6.3		Fine Delta = 17.7	
	Coarse Delta / Fine Delta = 6.3/17.7 = 0.36			

The data analysis found no discernible trend between density and permeability for coarse mixes. As described earlier, NCAT has published recommended criteria for coarse-graded Superpave mixes. An analysis was conducted to determine if these criteria are achievable. Table 2.10 provides a frequency and percentage of all coarse-graded test sites that met, or failed to meet, recommended NCAT permeability and density thresholds. For all criteria combinations, a large percentage of failure occurred. Less than 20% of the criteria were met.

Table 2.10 Pass/Fail Results for Coarse-Mix WisDOT Projects applied to NCAT Recommended Permeability Criteria

Criteria (1)	K x 10^{-5} cm/sec (2)		%Gmm (3)	
(a) 9.5-mm NMAS				
Pass	5	83%	1	17%
Fail	1	17%	5	83%
Total	6	100%	6	100%
(b) 19-mm NMAS				
Pass	1	6%	1	6%

Fail	16	94%	15	94%
Total	17	100%	16	100%
(c) 25-mm NMAS				
Pass	0	0%	2	13%
Fail	15	100%	14	87%
Total	15	100%	16	100%

Similar to fine mixes, a beginning approach to establish a maximum permeability level would be to calculate the median value that produces a 50%/50% pass/fail percentage. Table 2.11 provides cross-classification for all pooled data, source, and Ndes. Data from the USH-20 Rockford, Illinois Ndes=70 mix was combined with the Ndes=75 data from STH-17. Best-fit regression equations are provided to determine required density.

Table 2.11 Median "k" Values for Coarse-Mix Projects

Level (1)	Number of Samples (2)	k x 10^{-5} cm/sec (3)	Regression Equation (4)	R^2 (5)	Density Required, % (4)
(a) All Data					
- - -	38	913	Regression Equation Not Significant	---	---
(b) Source					
Limestone	31	718	Perm. = 11950 - 120.2xDensity	17.8	93.5
Gravel	7	2,790	Perm. = 164029 - 1694.4xDensity	66.2	95.2
(c) Ndes					
75	24	1,100	Regression Equation Not Significant	---	---
100	6	199	Perm. = 7718 - 80.4xDensity	23.6	93.5
125	8	1,560	Regression Equation Not Significant	---	---

2.5 Summary of Findings from Field Study

Table 2.12 summarizes permeability and density results from the field study. Based on the fine-graded mix data, higher Ndes limestone-source mixes were more permeable. It was also determined that t/NMAS ratio was influential in achieving density below a ratio of 2 for gravel sources and ratio of 3 for limestone sources. A “tapering effect” was observed for limestone-source mixes outside the current WisDOT thickness-to-NMAS range of 3 to 5, where it was more difficult to achieve density below a ratio of 3, and possible to achieve a 92% density above a ratio of 5. Limestone-source fine mixes were more difficult to compact on a rigid PCC base. There were several factors that affected density growth, including mat temperature, number of passes, and their interaction. Layer thickness was a factor on a project-specific basis, with some projects indicating it was significant and others not significant.

Table 2.12 Summary of Field Study

Variable (1)	Fine-Graded Mixes (2)	Coarse-Graded Mixes (3)
Base	More difficult to compact on PCC base and higher Ndes-level mixes, yielding a more permeable pavement.	CABC was more permeable; only one project constructed on CABC.
Source	Limestone source was more permeable for high Ndes=100 mixes.	Confounded data; no statistical determination possible.
Density	Limestone source affects density, but no trend was observed for gravel.	No effect on permeability.
Ndes	Higher Ndes levels were more permeable.	Confounded data with no determination possible.
Thickness	Limestone sources had lower density than gravel for similar thickness. Thickness was an inconsistent factor affecting density growth.	Inconsistent factor for density growth.
NMAS	No effect on density and permeability.	No effect on density and permeability.

Passing No. 8 Sieve	Fine mixes with 40-45% Passing No. 8 sieve were more permeable than >45% Passing No. 8 sieve.	Coarse mixes with <40% Passing No. 8 sieve were more permeable than fine mixes with >40% Passing No. 8 sieve.
Thickness/NMAS	Limestone with lower ratios was less permeable. Gravel had no trend.	No effect on density and permeability.
Aggregate Ratios	A small Coarse Delta / Fine Delta Ratio was more permeable.	No determination made.
Mat Temperature	Higher temperatures help achieve greater density gain.	Higher temperatures help achieve greater density gain.
Number of Passes	More passes help achieve greater density gain.	More passes help achieve greater density gain.

One aggregate ratio has the potential to control permeability of fine-grades mixes: Ratio of (%P1/2 - %P3/8) / (%PNo.4-%PNo.8), referred to as the "Coarse Sieve Delta / Fine Sieve Delta Ratio". High ratios produced lower permeability. In addition, higher permeability results as the gaps increase between coarse aggregates (%P1/2" and %P3/8") and fine aggregates (%P4 and %P8), respectively. This suggests relative differences in these sieves may have an effect on internal void structure, and measured permeability, of the compacted material. The mix design could be controlled to a sufficient ratio to withstand permeability by either reducing the difference between the coarse sieves, fine sieves, or both.

For both fine and coarse mixes, an interactive relationship was found between density, permeability, and thickness where density was more difficult to achieve on thinner mats, however, density had no little effect on permeability for fine mixes and no effect on coarse mixes.

Based on limited coarse-graded data collected in this study, a clear relationship between layer thickness and permeability was not established. For the thickness/NMAS ratio, smaller ratios for limestone-source mixes appear more permeable than higher ratios, and no trend was observed with the gravel-source mix.

CHAPTER THREE

LABORATORY DATA ANALYSIS AND DISCUSSIONS

3.1 Introduction

This chapter provides details of the laboratory testing procedures used in this project, the results collected, and the data analysis followed. The lab testing procedures include the measurement of density and permeability of field cores, the alternative for the SGC specimen compaction methods, and the proposed procedure for testing the permeability of the lab compacted specimen and estimating the permeability of the field specimen. The results of the study include the lab density and permeability of field cores, and the lab density and permeability of SGC specimens. Based on the testing results, the analysis such as, correlation between field density and lab density, correlation between field permeability and lab permeability, and correlation between lab permeability of field cores and SGC specimens, are covered in this chapter.

3.2 Field Cores Permeability Testing

3.2.1 Equipment and Methods

In the laboratory, field cores and loose mix samples were taken from field projects. The cores were used to measure the density using the vacuum sealing method by the Corelok Device. All field cores were completely dried at room temperature before measuring the density with the Corelok. The loose mix samples were used to measure the maximum specific gravity (Gmm). It was determined that the Gmm measured in the lab using the Corelok is essentially similar to the Gmm measured in the plant using the ASTM D 2041.

To measure laboratory permeability of field cores, a flexible-wall permeameter and a pressure panel board following the methods described in ASTM D 5084-01 (Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible-Wall Permeameter), was used. A flexible-wall permeameter used in ASTM D 5084 is shown in Figure 3.1. The specimen is placed between two caps (upper and lower caps) in a cell filled with water. A latex membrane is used to seal the specimen to the caps and to isolate the specimen from the water in the cell. Tubing is routed to the upper and lower caps for flowing water through the specimen. Water in the cell is used to apply stress to the specimen and to ensure that the membrane remains in tight contact with the specimen. Tight contact is critical because it prevents flow along the interface between the specimen and the membrane.

A pressure panel board is attached to the permeameter for delivery of water at specified pressures and for measuring the rate at which the water flows. A pressure panel typically consists of at least three burettes and a variety of regulators and valves for distributing the water and controlling the applied pressures. A schematic of a pressure panel is shown in Figure 3.2. One burette is to measure volume changes that occur within the cell. The other two burettes are used to measure the rate of flow into and out of the specimen. The regulator associated with each burette is used to control air pressure applied on top of the water in the burettes, and thus controls the water pressure in the cell or the inflow and outflow lines.

Before the specimen is permeated, it is saturated using a technique called “back-pressuring”, which consists of incrementally increasing the cell pressure and the influent and effluent pressure in equal amounts until the specimen becomes saturated. The elevated pore water pressure in the specimen (caused by the applied “backpressure” at the influent and effluent ends) forces water into small air-filled pores, collapses air bubbles, and enhances the rate at which air bubbles diffuse into the water. By incrementing the cell pressure and pore water pressures in equal amounts, the net stress (cell pressure-pore water pressure) acting on the specimen is unchanged. This stress is referred to as the “effective stress” in geotechnics.

The check for saturation during back-pressuring uses Skempton’s B coefficient for particulate materials (Skempton 1954). Skempton’s B coefficient is the ratio of the rise in pore water pressure (Δu) relative to an incremental change in the cell pressure (Δp_c) when the valves on the inflow and outflow lines (Figure 3.2) are closed:

$$B = \frac{\Delta u}{\Delta p_c} \qquad (3.1)$$

In theory (Skempton 1954), an increase in the cell pressure will result in equal change in pore water pressure in a particulate specimen that is saturated and from which drainage is prevented; i.e., the B coefficient will be 1. This condition prevails since the solids and water are essentially incompressible, the water is a continuum, and the solids are individual particles. In reality, particle-to-particle contacts preclude the B-coefficient from ever reaching 1.0 (Bishop and Eldin 1950) and specimens with $B \geq 0.95$ are generally accepted as saturated (Daniel 1994).

Cementation, as in HMA, can further reduce the B-coefficient at saturation. For such materials, a reasonable threshold for B at saturation can be assessed by measuring the B-coefficient daily, followed by a concurrent and equal increment in the backpressure and cell pressure (typically the increment is 35 kPa). At some backpressure, the B-coefficient will cease increasing, and this threshold value corresponds to saturation. No general threshold value for B has been established for HMA. Thus, based on the initial testing results, the common criterion of $B \geq 0.95$ appears reasonable for testing HMA.

The hydraulic gradient (i) is applied after the specimen has been saturated through back-pressuring. The hydraulic gradient is the ratio of the drop in total head across the specimen (ΔH) to the length of the specimen (L); i.e., $i = \Delta H/L$. Several methods can be used to apply the hydraulic gradient; they differ in how the difference in total head across the specimen is controlled. The methods in D 5084 are (i) the constant head method (Method A), (ii) the falling-head method (Method B), and (iii) the falling-head rising-tail method (Method C). In this study, the falling head-rising head method (D 5084-Method C) was used since it is easily implemented while applying backpressure to the specimen. In this method, the total head on the influent end of the specimen decreases while the total head on the effluent end increases. Thus, the difference in total head across the specimen decreases during the test. The changes in the drop in total head are read directly off the burettes as changes in the water levels. The permeability (K) is computed using the following (Daniel 1989):

$$K = \left(\frac{a_1 a_2}{a_1 + a_2}\right)\left(\frac{L}{A(t_2 - t_1)}\right)\ln\left(\frac{\Delta H_1}{\Delta H_2}\right) \tag{3.2}$$

where a_1 and a_2 are the cross-sectional area of inflow and outflow burettes, respectively, A is the cross-sectional area of the specimen, and ΔH_1 and ΔH_2 are the differences in total head across the specimen at times t_1 and t_2 respectively.

Ideally the hydraulic gradient should be selected as close as possible to the value expected in the field. For pavements, the gradient is likely to be close to one since appreciable ponding on the surface does not occur and gravity is the primary mechanism driving flow. However, testing times can be long when a hydraulic gradient near one is used, especially for less permeable materials. ASTM D 5084 provides guidelines on maximum values for the hydraulic gradient that depend on the anticipated permeability. However, these guidelines were developed for soils, which are softer than HMA and thus are more susceptible to compression caused by seepage pressures. Based on the initial results of the permeability testing of HMA, an intermediate hydraulic gradient of 18 was used for this study.

During the test, water is allowed to flow through the specimens for three times, and hence, three permeability readings are measured at the steady state. The average value of the three permeability readings is reported. However, it should be noted that duplicate testing, using two different specimens of the same mix, is not conducted because of the difficulty in obtaining duplicate specimens that has the exact same density and distribution of the voids.

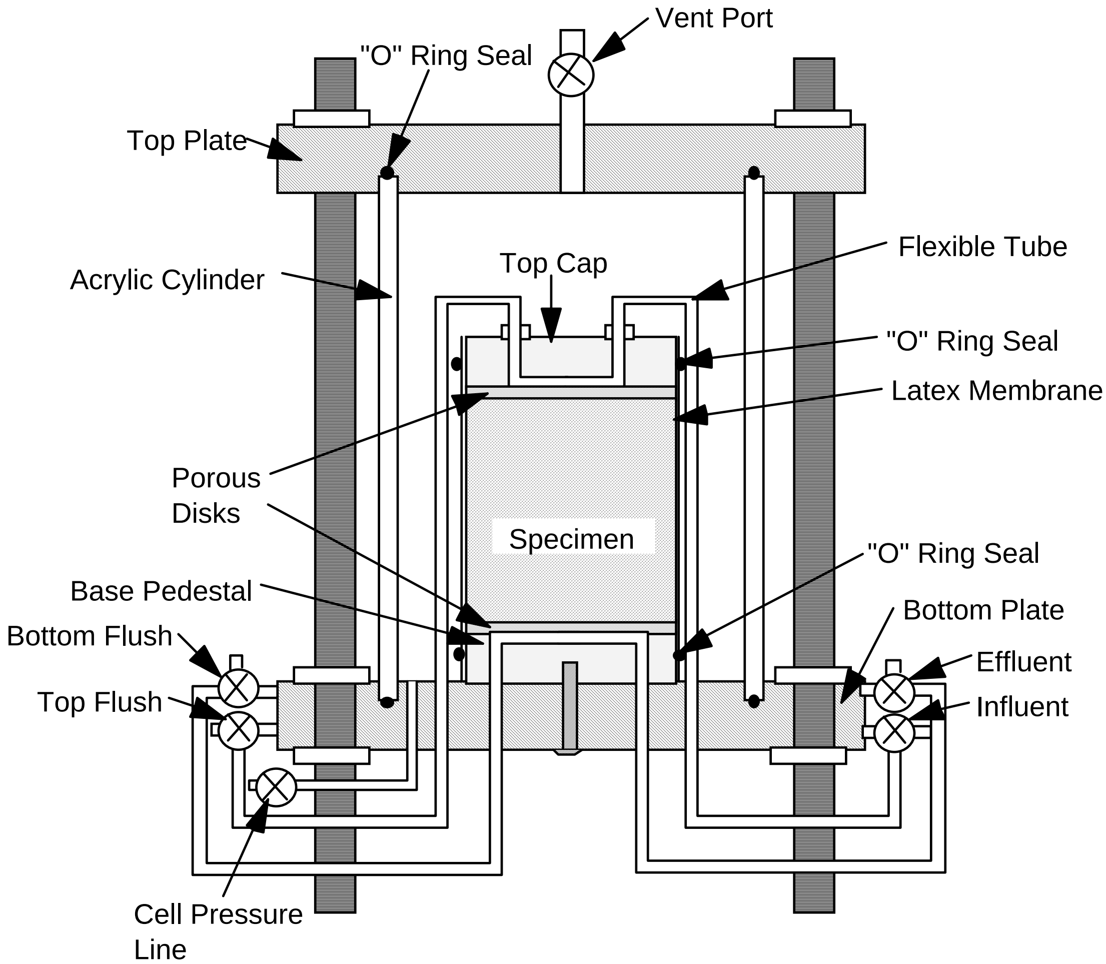


Figure 3.1 Flexible-Wall Permeameter Used in ASTM D 5084

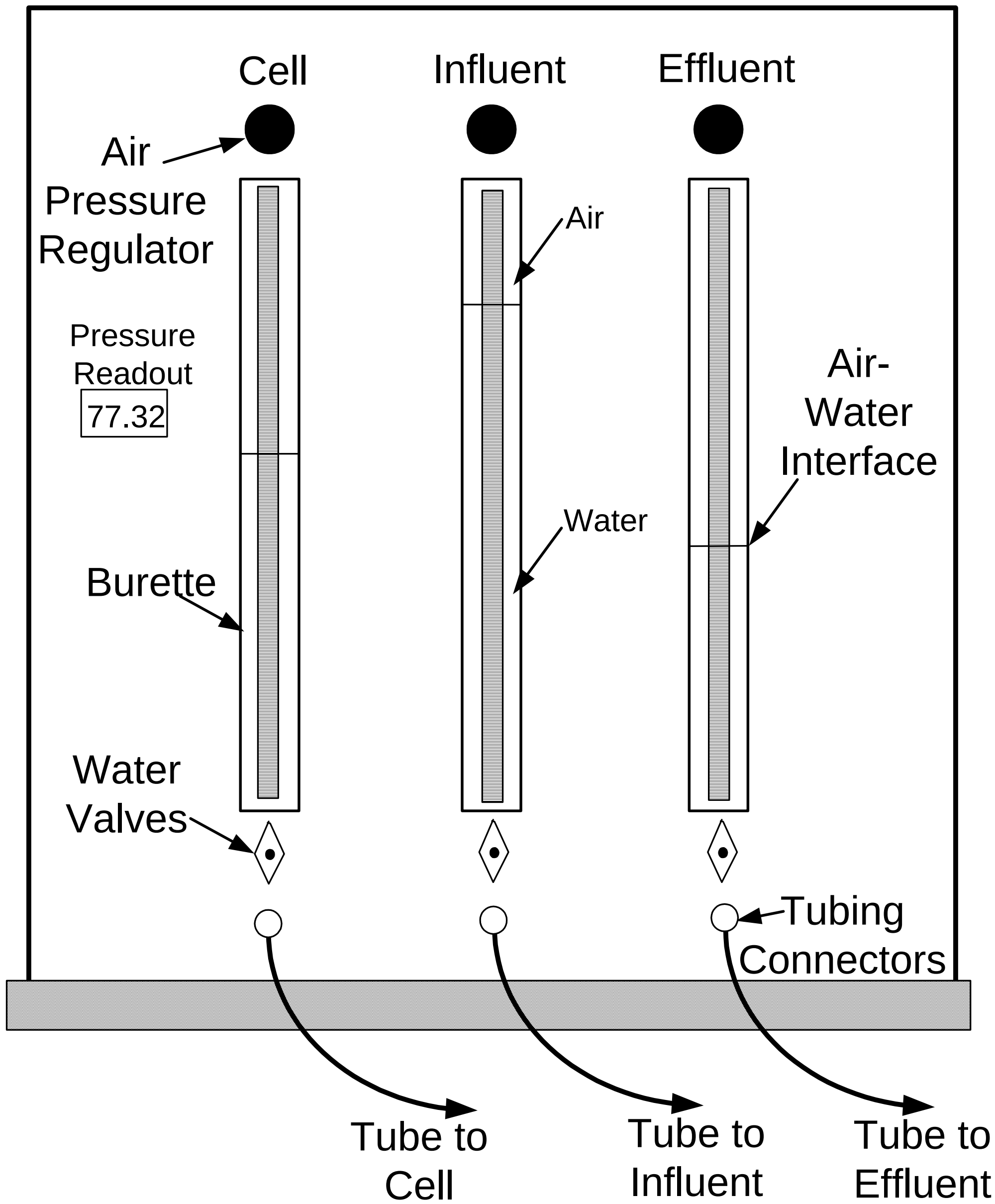


Figure 3.2 Pressure Panel Used in ASTM D 5084

3.2.2 *Density and Permeability Results*

Table 3.1 includes a summary of the field and laboratory results for density and permeability. The laboratory results are for the field cores specimens, not the specimens compacted in the laboratory using the SGC, which will be covered in a later section.

Table 3.1 Summary of All Test Results

Project	Site	Layer Thickness (cm)	Field Data		Field Cores Data	
			Field Density (Nuclear Gauge) (%)	Field Permeability (NCAT Device) ($x\ 10^{-5}$ cm/s)	Lab Density (CoreLok Device) (%)	Lab Permeability (ASTM D5084) ($x\ 10^{-5}$ cm/s)
STH23U	1	3.5	93.77	8.23	92.71	25.40
	2	4.3	93.42	18.81	91.76	36.00
	3	5.5	93.20	11.33	93.66	21.70
	4	5.9	93.24	46.07	93.54	34.20
	5	6.1	92.26	46.45	92.51	47.90
	6	6.5	91.54	115.91	92.24	69.13
STH23L	1	7.9	91.10	21.02	91.84	35.27
	2	8.1	91.38	22.49	92.47	31.35
	3	4.2	90.63	64.81	90.58	41.67
	4	5.2	92.00	48.73	92.00	32.97
	5	3.4	90.22	77.97	90.35	59.97
	6	3.1	90.20	128.65	87.94	62.20
WiscU	1	3.8	92.25	34.88	91.47	38.45
	2	4.1	94.38	26.34	93.88	16.55
	3	6.0	90.63	220.14	91.82	52.73
	4	3.2	90.43	171.06	90.87	50.35
	5	6.4	92.24	39.10	92.57	19.50
	6	5.1	94.12	22.46	94.15	9.91
WiscL	1	7.9	94.62	58.05	95.69	0.09
	2	7.0	90.68	38.64	92.37	34.30
	3	6.4	93.31	186.06	92.99	45.00
	4	5.1	90.77	399.32	91.43	46.85
	5	4.5	92.40	21.83	93.58	9.75
	6	5.7	90.87	140.10	92.41	40.70
	7	5.1	83.22	2664.92	85.64	93.85
	8	3.8	86.27	1547.70	86.42	70.85
	9	3.2	85.36	2491.49	84.50	79.10
	10	3.5	89.94	62.57	91.70	46.03
	11	3.2	90.88	82.02	92.29	26.35
USH110U	1	4.8	92.83	50.11	92.23	30.75
	2	5.1	91.60	28.08	92.35	24.4
	3	3.5	92.07	27.39	92.03	27.95
	4	3.8	93.51	55.19	92.35	27.75
	5	3.5	92.90	15.86	93.90	5.53
	6	3.2	91.83	31.21	92.83	22.65
USH110L	1	2.9	93.03	5.32	92.67	5.91
	2	3.5	95.20	6.36	93.02	7.27
	3	4.5	91.77	14.94	92.76	20.65
	4	4.8	92.37	36.50	92.70	24.40
	5	7.3	92.10	53.10	93.38	23.95
	6	7.0	91.33	104.73	92.79	20.70
USH8U	1	6.0	91.44	318.46	91.56	71.9
	2	5.4	92.16	243.52	91.81	71.7
	3	6.0	92.73	153.89	92.94	40.3
	4	5.7	92.45	172.43	92.31	54.3
	5	3.8	91.48	129.15	91.72	50.9

	6	4.1	92.36	99.16	93.18	37.1
USH8L	1	3.8	93.04	116.19	92.85	100.3
	2	4.1	93.25	151.06	93.57	49.7
	3	4.8	93.86	145.25	93.08	51.6
	4	5.4	94.28	151.95	94.02	24.3
	5	6.4	93.71	315.97	94.10	35.4
	6	5.7	93.43	220.13	93.88	40.8
I894U	1	4.8	94.51	208.3	94.15	25.33
	2	4.1	94.82	98.9	93.61	56.60
	3	6.4	92.62	571.5	92.35	55.70
	4	6.4	91.83	725.4	92.94	49.30
	5	4.4	89.33	1880.5	87.60	97.97
	6	5.1	92.63	902.6	91.37	62.83
I894L	1	4.8	90.91	2006.65	90.33	91.00
	2	7.0	91.75	483.95	92.66	41.73
	3	7.0	93.18	876.03	93.20	72.27
	4	7.3	93.50	235.10	93.43	12.00
	5	9.5	93.45	627.15	94.33	0.41
	6	8.3	89.50	2586.68	91.14	72.13
STH21U	1	5.7	92.40	520.0	92.52	65.1
	2	5.4	91.94	778.2	91.71	96.5
	3	6.4	92.06	693.3	92.43	81.3
	4	5.7	93.29	564.9	92.57	84.7
	5	4.1	91.86	172.6	92.57	37.9
	6	4.4	91.30	273.8	90.65	73.9
STH21L	1	7.0	91.74	1014.29	89.86	70.1
	2	7.6	90.94	975.28	90.58	39.4
	3	7.6	91.47	954.99	90.60	90.8
	4	7.0	92.73	369.59	91.86	108.0
	5	7.0	91.74	333.25	91.38	105.0
	6	5.1	91.72	155.48	91.29	90.3
I94	1	10.2	93.86	1560.0	93.18	33.30
	2	10.2	91.60	2860.1	92.04	103.10
	3	11.8	93.24	793.8	93.65	27.23
	4	12.1	92.27	1567.5	91.76	31.47
	5	7.0	91.60	694.0	91.17	82.97
	6	7.0	93.43	167.1	92.12	9.0
USH20U	1	3.5	88.95	1465.9	87.54	83.10
	2	4.7	93.48	557.0	93.73	8.75
	3	4.6	92.59	208.5	92.97	53.0
	4	4.1	91.95	136.2	93.73	40.9
	5	3.5	93.10	75.2	93.37	25.9
	6	3.4	92.91	103.1	93.61	26.8
USH20L	1	2.2	91.50	976.4	83.53	48.8
	2	2.2	91.97	2114.1	82.46	29.6
	3	4.4	92.21	913.0	90.01	27.3
	4	4.4	90.53	1337.1	89.10	93.2
	5	6.4	92.12	1816.1	90.24	56.6
	6	7.0	90.90	3325.9	89.18	88.8
STH17	1	9.5	90.07	6023.52	94.11	35.2
	2	9.5	91.28	1099.18	96.23	3.83
	3	11.8	92.03	597.50	96.70	1.27
	4	11.1	91.70	3322.09	96.86	0.76
	5	11.1	92.81	2789.17	96.54	2.52
	6	11.8	90.52	11187.43	94.62	57.0

3.3 Laboratory Compacted Specimen Testing

The laboratory work also included production of compacted mixture samples from loose mixtures using the Superpave Gyratory Compactor (SGC). The objectives were to better mimic aggregate orientation in the field, and to develop a tentative procedure to estimate permeability of field pavements. To achieve both of these objectives, two compaction procedures were evaluated. The following sections summarize the compaction procedure, the compaction results, and the permeability results of the SGC specimens produced by these compaction procedures. This section also includes recommendations to validate a protocol to estimate permeability in the lab of mixtures intended for construction in the field after completing the mix design.

3.3.1 Alternatives for Laboratory Compaction Method

Initially, the compaction procedure, called here "Method A", was selected to produce the SGC specimens that have the same air voids content as the field cores. It was assumed that because voids content is a major factor controlling permeability, the lab permeability of these specimens would be very similar to the field permeability. Method A is a trial and error procedure that can be summarized as follows:

<u>Method A</u>

After the field cores were taken to the laboratory, height (thickness) and Gmb of field cores were measured. The amount of loose asphalt mixtures was then calculated to produce SGC specimens that will have the same height and density at the specified number of gyrations. The equation to calculate the amount of material for the compaction is as follows:

$$Wt. = Gmb \times t \times A / 1000 \quad (3.3)$$

where Wt. is the amount of material (g), t is the height or thickness of field cores (mm), and A is the cross sectional area of the specimen (mm^2). The SGC specimens were compacted by controlling specimen height in the Superpave gyratory compactor. The Gmb was measured after the curing of compacted specimen for 24 hours at room temperature. If the density varies from the targeted density by ± 0.5%, another SGC specimen will be compacted by adjusting the specimen height until the targeted density is achieved at the field core thickness (height). The compaction by Method A resulted in the SGC specimens with approximately the same density and thickness as the field cores. However, the number of gyrations had to be varied depending on the mix type or source, the targeted density and thickness. The ASTM D5084 was used to measure the lab permeability of these SGC specimens.

Figure 3.3, shows the relationship between the lab permeability of the specimens produced by Method A using the SGC compactor and the permeability of field cores measured by the same method in the lab. As shown in Figure 3.3, the permeability of the SGC specimens are generally lower than the field cores and there is very high scatter in the results indicating the lack of good correlation between the two measures. To determine the cause of difference between lab permeability of field cores and lab permeability of SGC specimens, Method B was proposed to evaluate hypothesis that the difference in the lab permeability of field cores and the permeability of SGC samples are due to different aggregate orientation which could be resolved by changing amount of material placed in mold as explained by Dr. Erv Dukatz of Mathy Construction.

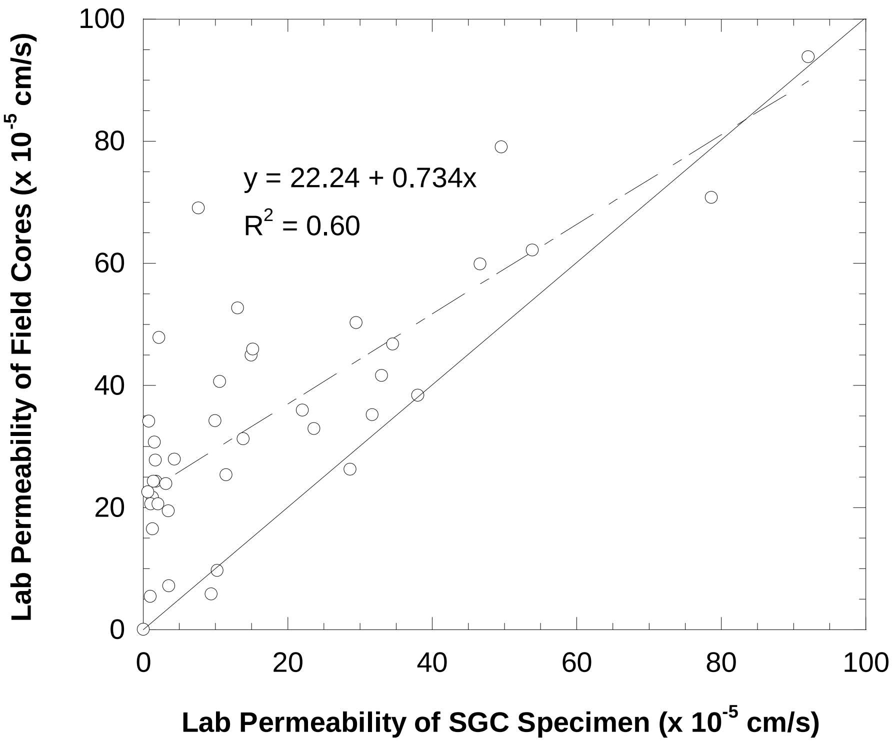


Figure 3.3 Relationship between lab permeability of field cores and SGC specimens.

One project (the STH23-lower mix) was selected as a trial mix for the compaction using Method B. The compaction using Method B can be summarizes as follows:

Method B

In this method, the loose asphalt mixture was used to compact different sample sizes but using the same number of gyrations. At least three specimen sizes were selected based on the range of field cores density and thickness. The number of gyrations was fixed at Ndes = 75 gyrations. The compaction by Method B results in the SGC specimens within the range of same density as in the field cores but varied in the specimen thickness. Similar to specimens produced by Method A, the ASTM D5084 was used to measure the permeability for SGC specimens. The lab permeability of these SGC specimens was found to be close to the lab permeability of field cores and to be within the same range of density. Figure 3.4 shows the comparison of the lab permeability between the field cores and the SGC specimens compacted by using Method A and Method B for the selected project. The results show that Method B, which is a compaction at fixed number of gyrations at Ndes, is giving the best alternative for the compaction to simulate the field specimens.

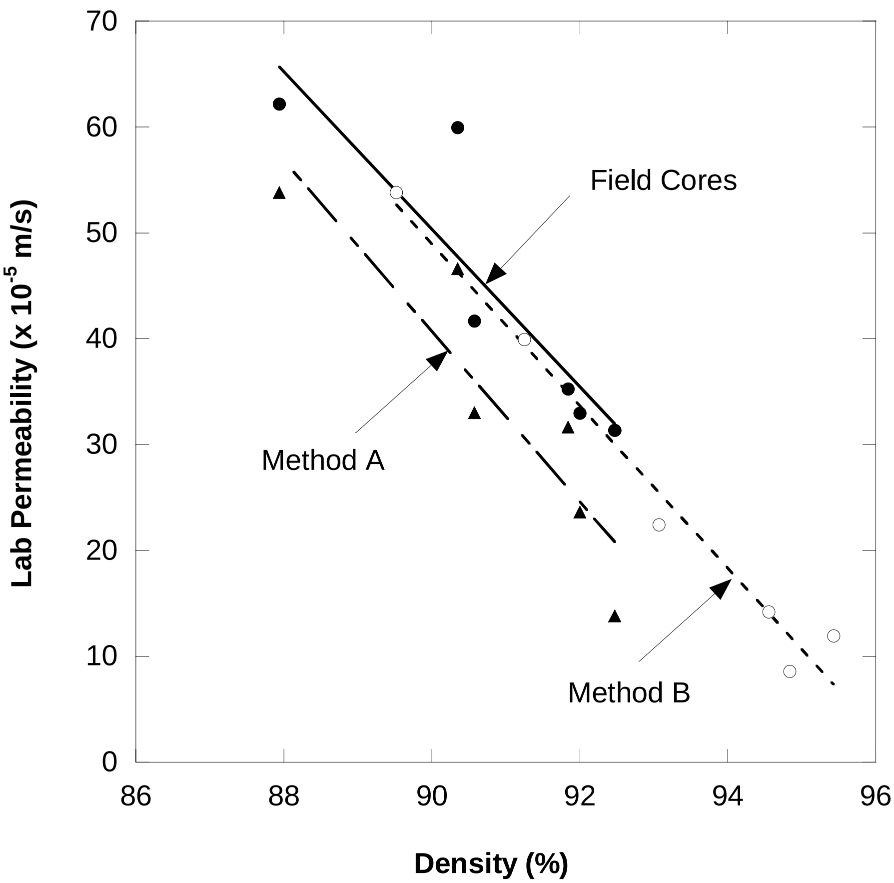


Figure 3.4 Lab permeability of field cores and SGC specimens compacted by Method A and Method B (STH23-Lower Mix)

3.3.2 Proposed Compaction Procedure

Based on the comparison of the results for Methods A and B, method B was used for the laboratory study in the remaining of this project. The detailed steps of the procedure includes 4 steps, as follows:

Step 1: Based on the mix design process, the loose asphalt mixture (field-mixed) was obtained from particular field project. In this study, the loose mix collected from field study as indicated in Chapter 2 was used.

Step 2: At least three SGC specimens were compacted to Ndes, which is depending on the mixture type. The amount of material used to produce different sizes of specimens was in the range of 1000 to 4000 g.

Step 3: Density (%Gmm) and lab permeability of these specimens were measured after the compaction was completed. Figure 3.5 shows an example for the plot of density versus lab permeability of SGC specimens.

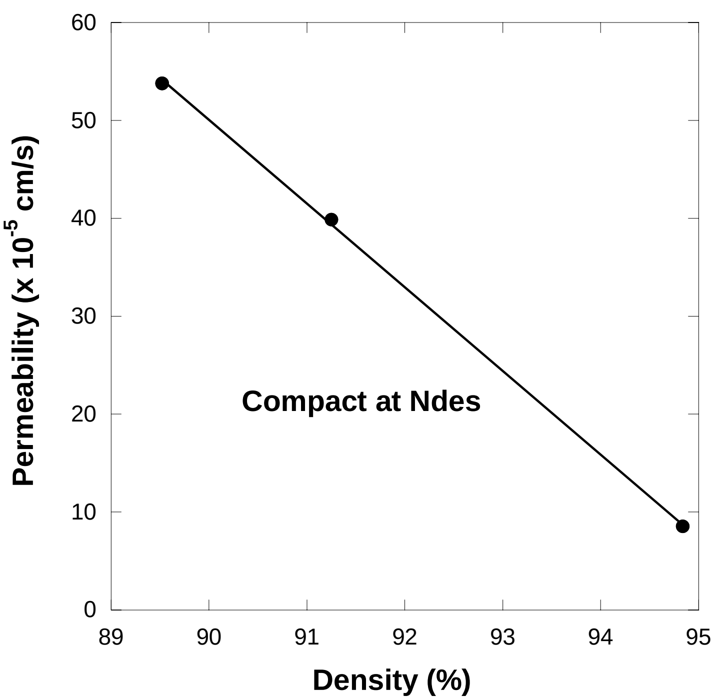


Figure 3.5 Density vs. Lab Permeability

Step 4: Since the targeted field density is known, the permeability can be predicted based on Figure 3.5. For example, if the targeted field density is 92% Gmm, the predicted permeability in the field is approximately 32 x 10^{-5} cm/s.

The procedure was used for several other projects included in this study. The predicted permeability values are plotted versus the measured permeability of field cores as shown in Figure 3.6. The relationship between predicted and measured permeability confirm that the procedure show a very good potential.

To further validate the proposed procedure, a total of 16 mixes as listed in Chapter 2 were compacted and the permeability was measured as described in Step 1 to 3. It should be noted that the specimen thickness is considered as a secondary factor, because it is normalized in the analysis of the permeability test results. Therefore, the density, which is a main factor affecting permeability, was targeted to estimate the permeability.

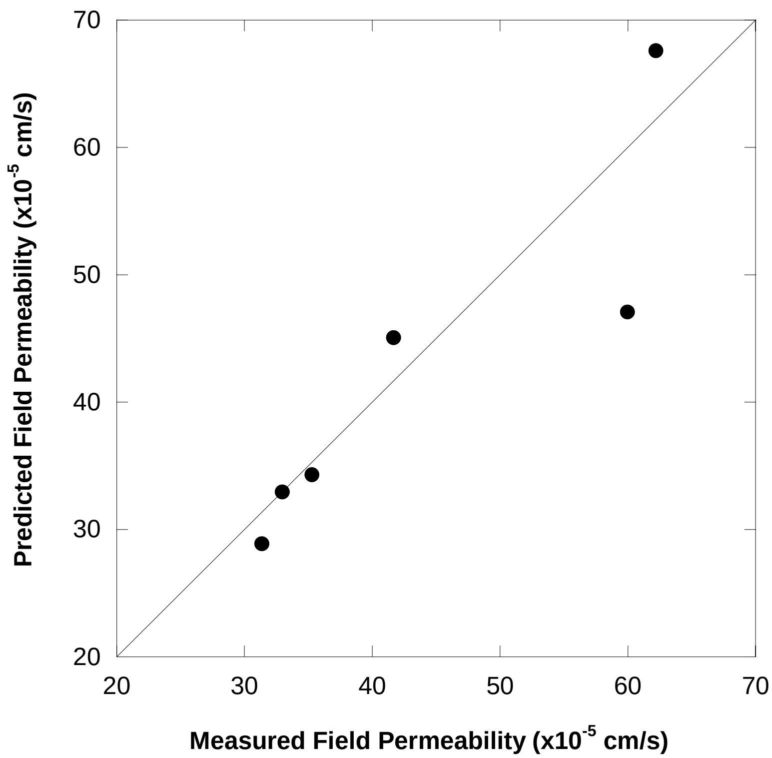


Figure 3.6 Predicted vs. Measured Field Permeability

3.3.3 Density and Permeability Results

The density and the lab permeability results of all SGC specimens that were produced and tested according to Method B are summarized in Table 3.2. The table is organized according to project. As can be seen in the table, the projects included various Ndes values, multiple thickness and density values. For each project a minimum of 2 SGC samples of different thickness was produced and used to predict permeability. The relationship between the field and laboratory density and field and laboratory permeability are discussed in section 3.4 as part of the analysis.

Table 3.2 Summary of density and lab permeability results of all SGC specimens

Project	Ndes	Field Cores			SGC Specimens		
		Thickness (cm)	Density (%)	Permeability ($x\ 10^{-5}$ cm/s)	Thickness (cm)	Density (%)	Permeability ($x\ 10^{-5}$ cm/s)
STH23U	75	3.5 4.3 5.5 5.9 6.1 6.5	92.71 91.76 93.66 93.54 92.51 92.24	25.40 36.00 21.70 34.20 47.90 69.13	3.7 4.2	92.38 93.77	27.63 13.70
STH23L	75	7.9 8.1 4.2 5.2 3.4 3.1	91.84 92.47 90.58 92.00 90.35 87.94	35.27 31.35 41.67 32.97 59.97 62.20	2.6 3.7 7.5	89.52 91.25 94.84	53.80 39.90 8.54
WiscU	75	3.8 4.1 6.0 3.2 6.4 5.1	91.47 93.88 91.82 90.87 92.57 94.15	38.45 16.55 52.73 50.35 19.50 9.91	2.6 3.7 4.8	90.68 92.77 94.67	44.40 27.40 22.20
WiscL	75	7.9 7.0 6.4 5.1 4.5 5.7 5.1 3.8 3.2 3.5 3.2	95.69 92.37 92.99 91.43 93.58 92.41 85.64 86.42 84.50 91.70 92.29	0.09 34.30 45.00 46.85 9.75 40.70 93.85 70.85 79.10 46.03 26.35	2.7 3.7 5.6	87.67 91.78 94.60	67.73 53.13 42.13
USH8U	75	6.0 5.4 6.0 5.7 3.8 4.1	91.56 91.81 92.94 92.31 91.72 93.18	71.9 71.7 40.3 54.3 50.9 37.1	2.7 3.8 4.9	88.33 90.64 92.31	60.37 52.57 23.77
USH8L	75	3.8 4.1 4.8 5.4 6.4 5.7	92.85 93.57 93.08 94.02 94.10 93.88	100.3 49.7 51.6 24.3 35.4 40.8	2.7 3.8 6.1	90.63 92.39 94.64	63.87 39.83 17.20
I894U	100	4.8 4.1 6.4 6.4 4.4 5.1	94.15 93.61 92.35 92.94 87.60 91.37	25.33 56.60 55.70 49.30 97.97 62.83	3.7 4.8 5.9	89.50 93.13 94.89	67.57 50.50 46.83
I894L	100	4.8 7.0 7.0 7.3 9.5 8.3	90.33 92.66 93.20 93.43 94.33 91.14	91.00 41.73 72.27 12.00 0.41 72.13	5.0 6.1 8.3	89.39 91.92 94.02	80.73 79.30 16.37
STH21L	100	7.0 7.6 7.6 7.0	89.86 90.58 90.60 91.86	70.1 39.4 90.8 108.0	2.7 3.7	89.00 92.10	53.77 62.53

		7.0 5.1	91.38 91.29	105.0 90.3			

3.4 Correlations of Lab and Field Results

The analysis included in this study cover density and permeability results. For each of these two properties, three types of measurements were collected. They include field measurements taken on the surface of the pavement, laboratory measurements taken for field cores, and laboratory measurements for specimens produced in the lab using the SGC. The following sections include the correlations determined between pairs of these measurements as determined to be relevant to the objectives of the project.

3.4.1 Correlation between Field Density and Lab Density

Figure 3.7 shows the comparison of the density measured in the field by using the nuclear gauge and the density measured in the lab by using the Corelok device. The results plotted indicate that there is generally a good relationship between these two measures. It is also observed that the scatter around the equality line is within the 95% upper and lower bounds, which is an acceptable range due to inherent variability in field studies.

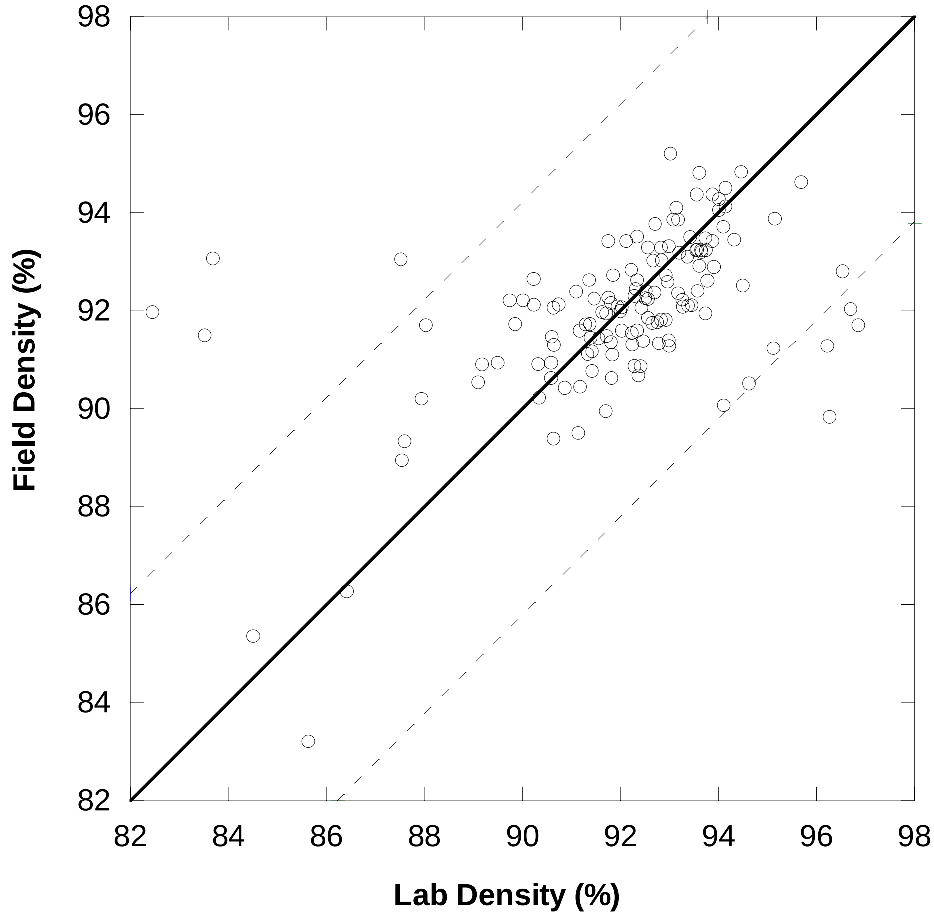


Figure 3.7 Relationship between field and lab density

3.4.2 Correlation between Field Permeability and Lab Permeability of Field Cores

As shown in Table 3.1, the laboratory permeability was measured for all field cores taken from all projects. Figure 3.8 shows the relationship between the field measurements taken on the surface of the pavement using the NCAT device and the lab permeability measured on field cores for both fine-graded and coarse-graded mixes. Although a line of equality was expected in the relationship, it is clear from Figure 3.8 that the field permeability values of most pavements are higher than the lab permeability by a significant margin ranging between 10 percent and 100 percent. This result can be explained by the fact that water during field permeability testing can flow in lateral directions, while in the permeability measurement in the lab water can only flow vertically due to the surrounding membrane.

In the fine-graded mix, despite the wide scatter, and the differences in values, there exists a relationship (R^2 = 0.49) between the lab and the field measurements as shown in Figure 3.8. This relationship although not very strong, there is a strong trend and thus can possibly be used as a method for the estimation of the field permeability based on the lab permeability.

In the case of coarse-graded mixes however, the differences between the lab and the field permeability are much higher than in the fine-graded mix. In addition, a very poor trend is found for the relationship between these measurements. This could be explained by the reason that the coarse-graded mix generates rougher pavement surface than the fine-graded mix, and then, the gasket seal applied underneath the NCAT field permeameter cannot be perfectly sealed on the rough surface of coarse mixes. Therefore, the water could leak along the sides of the sealant gasket resulting in higher, and possibly inaccurate permeability values.

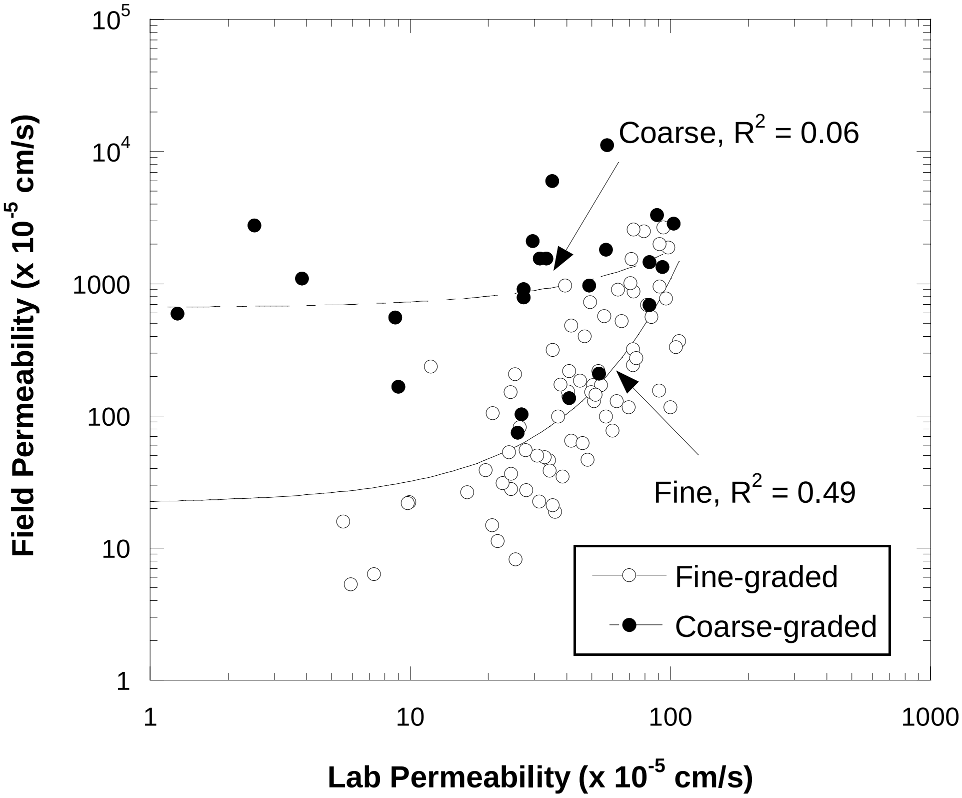


Figure 3.8 Relationship between field permeability and lab permeability of coarse- and fine-graded mixes

These results raised the question of whether the use of NCAT permeameter is a valuable method to measure permeability in the field. Since it is found that the field permeability measured by the NCAT device correlates well to the true permeability measured in the laboratory for fine-graded mix, an attempt was made to differentiate between coarse- and fine-graded mixes, and to evaluate if the NCAT device is a good method to measure field permeability of unknown graded mixture.

The percent passing 2.36 mm sieve (P8) was selected as a criteria to identify the gradation of mixtures. All mixtures used in this study were classified into three main groups according to the percent passing 2.36 mm sieve as shown in Table 3.3.

Table 3.3 Classifications of the mixtures based on the percent passing 2.36 sieve (P8)

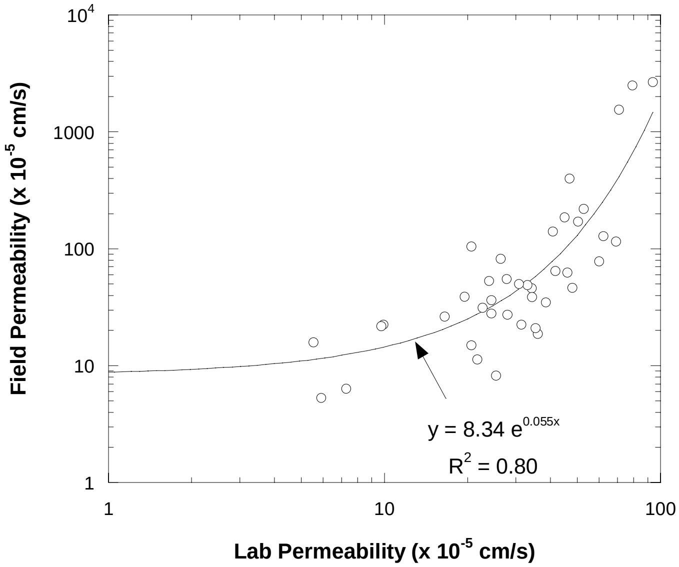
Percent passing 2.36 mm sieve	Mixture
> 45%	STH23U, STH23L, WiscU, WiscL, USH110U, USH110L
40-45%	STH21U, STH21L, I894U, I894L, USH8U, USH8L
< 40%	I94, USH20U, USH20L, STH17

Figure 3.9 shows three graphical plots for the relationships between field and lab permeability sorted based on the aggregate gradation type. For the mixtures containing P8 higher than 45%, Figure 3.9(a) shows that there is a strong relationship between field and lab permeability ($R^2 = 0.80$). In Figure 3.9(b), the R^2 values reduce to 0.10 as the P8 falls between 40% and 45%, and no correlation was found when the P8 is lower than 40% (Figure 3.9(c)). The exponential functions that best fit the data in three plots are:

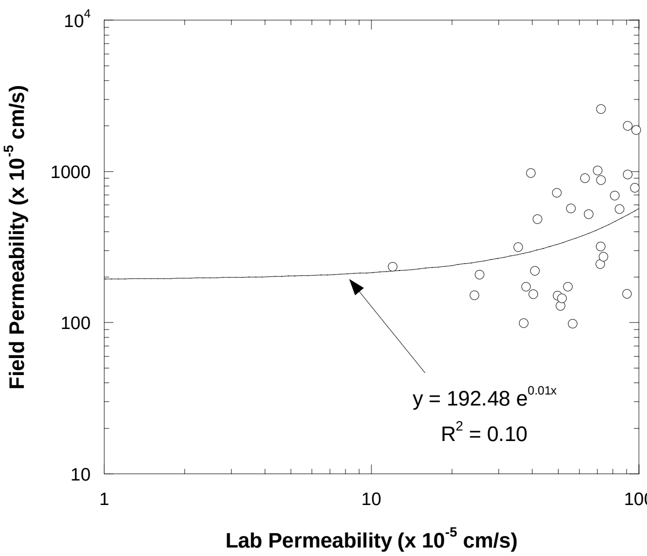
$$P8 > 45\%,\ \text{Field K} = 8.34 \times e^{0.055\,(\text{Lab K})} \qquad R^2 = 0.80 \tag{3.4}$$

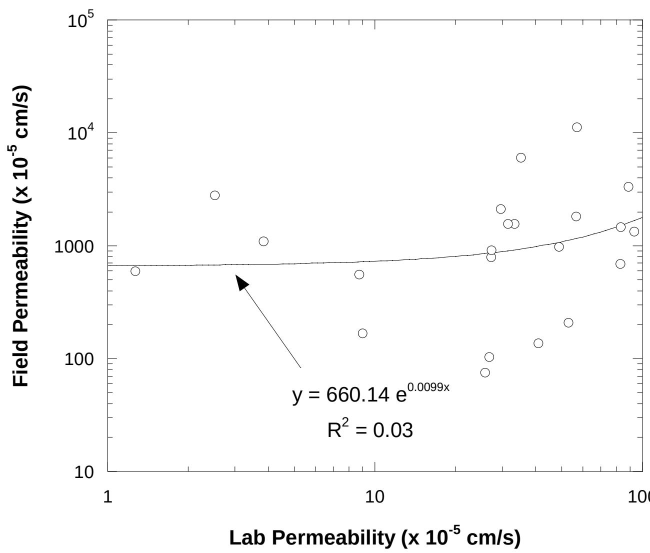
$$40\% < P8 < 45\%,\ \text{Field K} = 192.48 \times e^{0.01\,(\text{Lab K})} \qquad R^2 = 0.10 \tag{3.5}$$

where field K is the field permeability measured by the NCAT device, and lab K is the permeability of field cores taken from the field and measured in the laboratory using ASTM D5084 method.



a) Mixtures with P8 > 45%





b) Mixtures with 40% < P8 < 45%

c) Mixtures with P8 < 40%

Figure 3.9 Relationship between field permeability and lab permeability based on %passing 2.36 mm sieve

Based on the results provided in this study, it was observed that the permeability measured by the NCAT device gives a good correlation with the permeability measured in the lab, particularly for mixtures with P8 aggregate content higher than 45%. It is recommended that the measuring an index of permeability with the NCAT device can be: 1) appropriately used for fine-graded mixtures with P8 higher than 45%, 2) used with caution for fine-graded mixtures with P8 between 40-45%, and 3) not a good method for measuring the field permeability of mixtures with P8 lower than 40%.

3.4.3 Correlation between Laboratory Permeability of Field Cores and Predicted Permeability Using Lab Compacted Specimens

It is clear from the previous section that field permeability measured with the NCAT device cannot be assumed reliable in comparison to the permeability of field cores tested in the laboratory. However, in the case of fine mixtures there is a good correlation between field and lab permeability. The remaining question is if the field permeability of nine mixtures can be predicted from SGC compacted specimen. This question is important to answer because if the prediction is possible, then it can be included as part of the mixture design procedure. As indicated earlier in section 3.3, the SGC specimens were produced according to Method B. Figure 3.10 shows the comparison between the measured permeability values of field cores and the values predicted based on the SGC specimens. The best fit regression line, fitted with a zero intercept, has a slope of 0.763, as shown in the following equation:

$$\text{Predicted K} = 0.763\ (\text{Measured K for field cores}), \quad R^2 = 0.43 \qquad (3.6)$$

It is observed that the measured values are higher than the predicted values, particularly at higher permeability levels (> 50×10^{-5} cm/s). Also the slope of regression line is significantly different from the value of one, or the slope of equality line. The majority of the scatter is, however, close to the equality line, and falls within the 95% upper and lower bounds from the equality line. Therefore, although the regression trend does not match the equality, it is believed that this procedure could provide a reasonably acceptable estimate of the permeability.

These results support are not totally new because others conducting research in this area have also found similar trends. In a previous study at NCAT, reported by Cooley (2002), the authors have indicated that the SGC specimens could be used to estimate the permeability of the specimen compacted in the field.

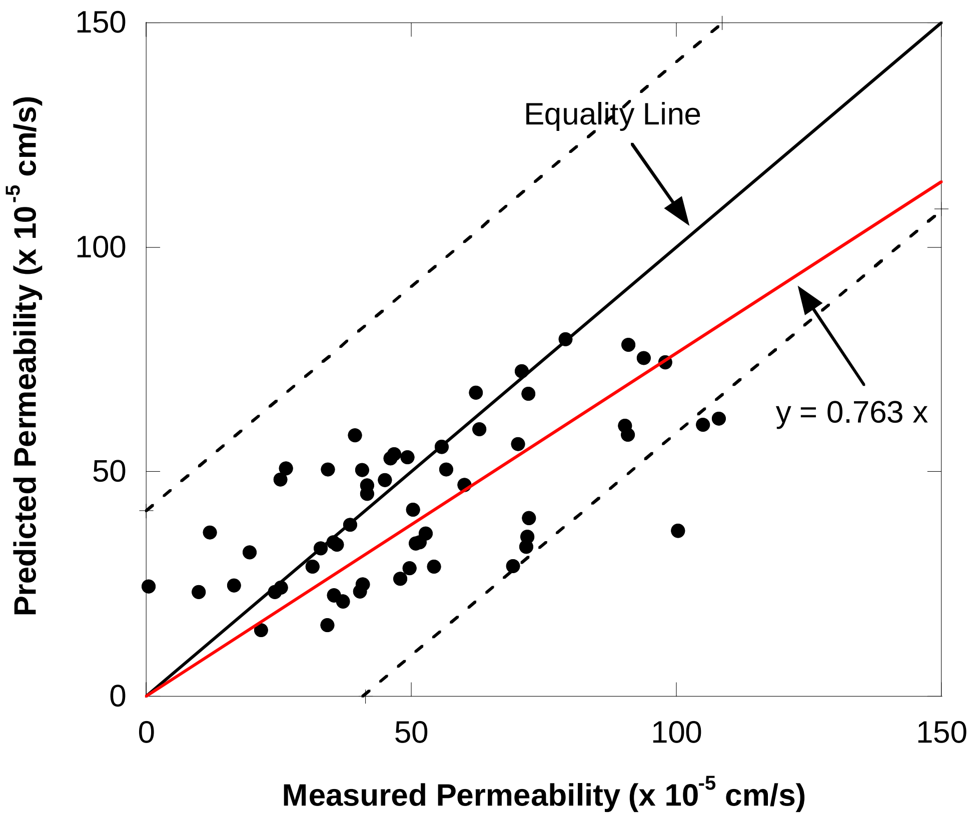


Figure 3.10 Predicted vs. Measured Permeability

3.5 Summary of Findings of Laboratory Study

The previous sections included a detailed presentation of all data collected in the laboratory study. The following points summarize the findings of this study.

1) There is a good relationship between the density measured in the field using the nuclear gauge and density measured in the lab using the Corelok Device. The nuclear gauge is therefore considered as an appropriate method to measure in-place density without damaging the pavement surface.

2) There is a good relationship between the field permeability and the laboratory permeability measured on field cores of fine-graded mixes with P8 higher than 45%. However, the relationship between the field permeability and the laboratory permeability measured on field cores of coarse-graded mix (P8 lower than 40%) is very poor. It should be noted that the NCAT permeability devices, with all its limitations, could possibly be used in the field (particularly for fine-graded mix with P8 higher than 45%) to measure an index related to true permeability values of field cores under well-controlled conditions. The true permeability is defined here as the values measured using the ASTM standards, which are recognized by many to be the best practice for granular materials. However, to measure the field permeability of coarse-graded mix (P8 lower than 40%), an approach to prevent water leakage along the sealant due to rough pavement surface should be established. The only other alternative that could be recommended at this time is to use cores extracted from the pavement and tested in the laboratory.

3) The lab permeability of SGC specimens, produced by Method B (constant number of gyrations with different sample sizes), provides a good prediction tool for the

lab permeability of field cores. Therefore, the use of Method B to produce the SGC specimen could be a good potential approach for including permeability criteria in the mixture design process.

CHAPTER FOUR

AIR AND WATER PERMEABILITY STUDY

This chapter presents the results of comparative air and water field permeability measurement of in-place asphalt pavement layers as well as a study of preferential flow paths and their relation to field and laboratory water permeability test results.

4.1 Development of Air Permeameter for Asphalt Pavements

In recent years, field permeability testing of in-place asphalt pavement was commonly performed with water-based, falling head permeameters such as the previously described NCAT device. Based on literature reviews conducted during the project proposal and initial study phases, the NCAT device was selected for use and deployed on initial field studies. Field permeability testing with this device identified a number of constraints which may inhibit the practical use of this device for field and/or acceptance testing of in-place pavements:

1. Permeability testing at any selected location is time consuming and labor intensive. Furthermore, a significant amount of water was necessary to initiate testing and large amounts of water are required to complete testing, particularly for coarse graded mixes with high permeability.

2. The NCAT permeameter requires an intimate seal between the pavement surface and the bottom of the device to eliminate water bleeding which would invalidate test results. This seal proved difficult to achieve and virtually impossible to verify during testing. Three separate sealing methods/materials were utilized throughout this study in an effort to achieve an adequate barrier to water bleed.

3. Repeated testing at selected test locations indicated a significant variation in permeability measurements, as indicated by changes in the time required to achieve a desired head change. Initially it was felt that these variations were the result of variable degrees of saturation during testing. However, after a number of tests conducted with pre-saturated pavements it was determined that the changing time intervals were more likely due to changes if the length of in-pavement flow paths which cannot be measured non-destructively during testing.

The ROMUS air permeameter was envisioned, designed and constructed during this project in an effort to eliminate the above constraints while still providing useful field measurements. The ROMUS device is based on the falling-head air permeameter principle with one noted exception: a vacuum chamber is used to draw air through the pavement as opposed to a pressurized chamber forcing air into the pavement. While fundamentally consistent with air flow measures of earlier devices, the vacuum chamber also serves to enhance the seal between the device and the pavement surface. This is in contrast to a pressurized chamber which must be ballasted to remain in contact with the pavement surface.

Figure 4.1 provides a schematic illustration of the ROMUS air permeameter and Figure 4.2 illustrates the completed device in position for field testing.

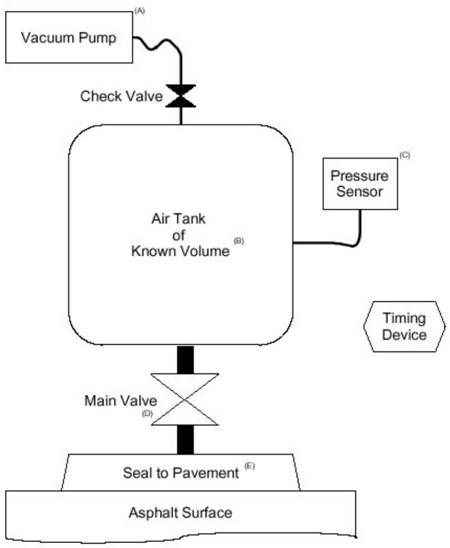


Figure 4.1 Schematic Illustration of ROMUS Air Permeameter

Figure 4.2 Illustration of the ROMUS Air Permeameter

The main components of the ROMUS air permeameter include a hand operated grease gun, base seal reservoir, vacuum chamber, automatic vacuum pump and valve, digital pressure gauge, and digital display. To initiate testing, the bottom of the ROMUS device is first sealed to the pavement surface by way of a grease seal. The sealant grease is manually pumped through the device into a recessed base ring which was sized to replicate the opening of the NCAT water permeameter and designed to eliminate problems observed with the various sealing techniques used for the NCAT device. Manually pumping of the grease through the recess ring appears to provide an efficient seal that can easily conform to the surface irregularities present on asphalt pavements of the type investigated during this study.

Once the device has been sealed to the pavement surface, pressing of the start button initiates a fully automated system that first creates a vacuum within the internal pressure chamber. When the vacuum pressure reaches a value of approximately 25 inches of water (47mm Hg), effectively simulating the maximum head of water used with the NCAT device, a valve automatically opens to allow air to be drawn through the pavement layer into the vacuum chamber. A timing system with a resolution of 1 millisecond initiates when the vacuum pressure reaches 24 inches of water and continually records the time until the internal pressure reaches 8 inches of water. For this research project, the ROMUS device was programmed to record four timing increments, each representing a change in vacuum pressure equivalent to 4 inches of water. This set-up simulates a falling head water permeability test with head drops from 24 – 20 inches, 20 – 16 inches, 16 – 12 inches and 12 – 8 inches. Once the test is complete, the four timing increments are displayed on a digital display for manual recordation. A full test sequence, including initial vacuum draw and four incremental measurements, can be completed in less than one minute.

Repeated testing with the ROMUS device indicates consistent results from one time increment to the next as well as from one test trial to the next. Figures 4.3 and 4.4 illustrate results from two sites located along USH 20. These sites were selected as representative of trials with both low and high permeability readings. Equivalent water permeabilities are displayed based on individual recorded time increments (24-20, 20-26, 16-12, 12-8 inches of water) as well as from the overall recorded time (24-8). As shown, the results are consistent across all test trials for both sites, with an overall coefficient of variation of 2.2% for the USH20U site and 7.7% for the USH20L site.

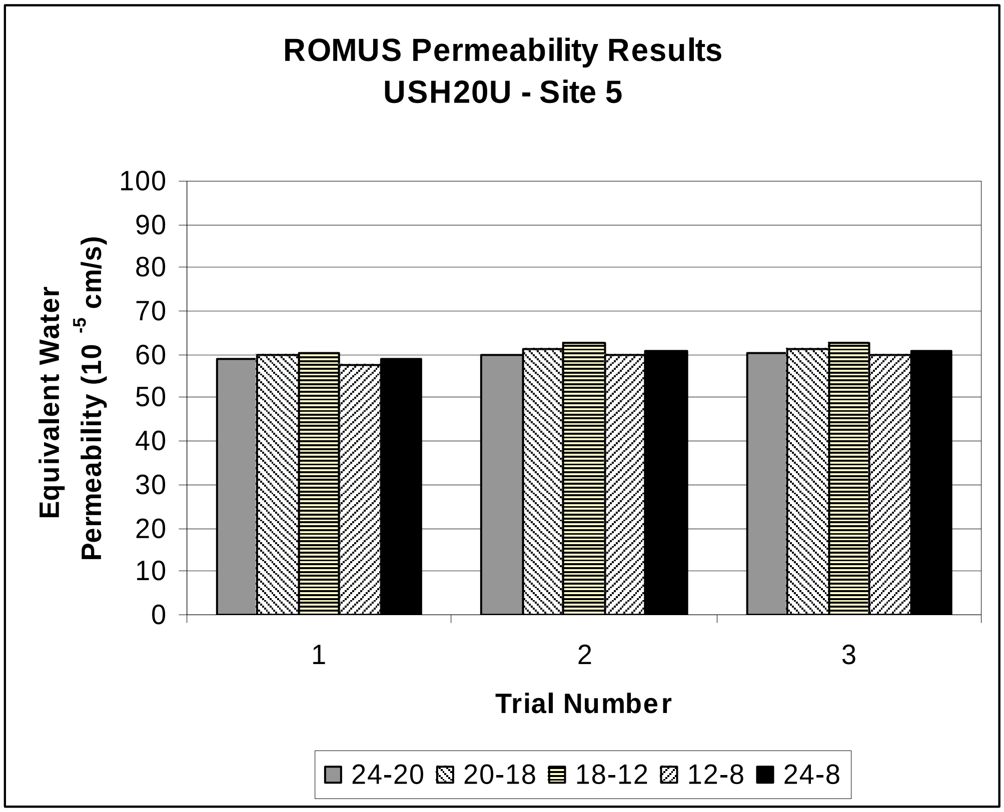


Figure 4.3 ROMUS Permeability Results for USH20U – Site 5

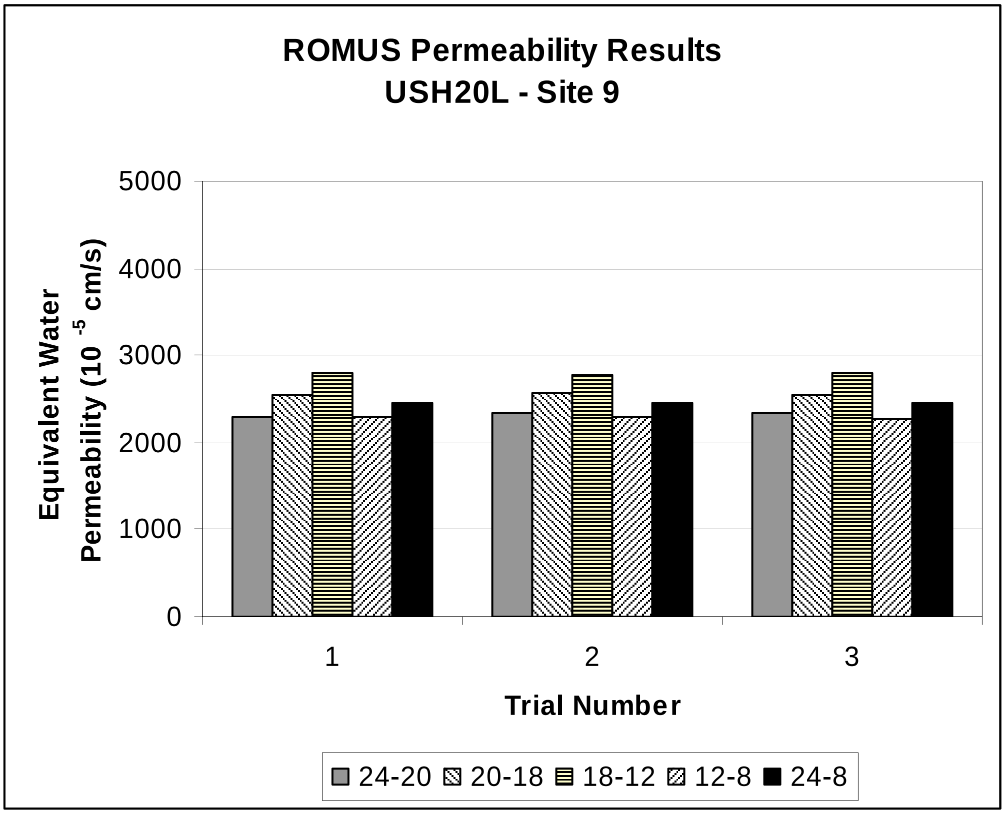


Figure 4.4 ROMUS Permeability Results for USH20L – Site 9

4.2 Comparison of Field Permeameter Readings

The ROMUS device was used in tandem with the NCAT device during testing on seven projects incorporating 72 test sites with ranging permeabilities. Figure 4.5 provides an aggregate comparison of equivalent water permeabilities measured by the ROMUS device versus NCAT water permeability readings. Figure 4.6 provides a grouped comparison of permeability readings based on gradation classifications described in Table 3.3.

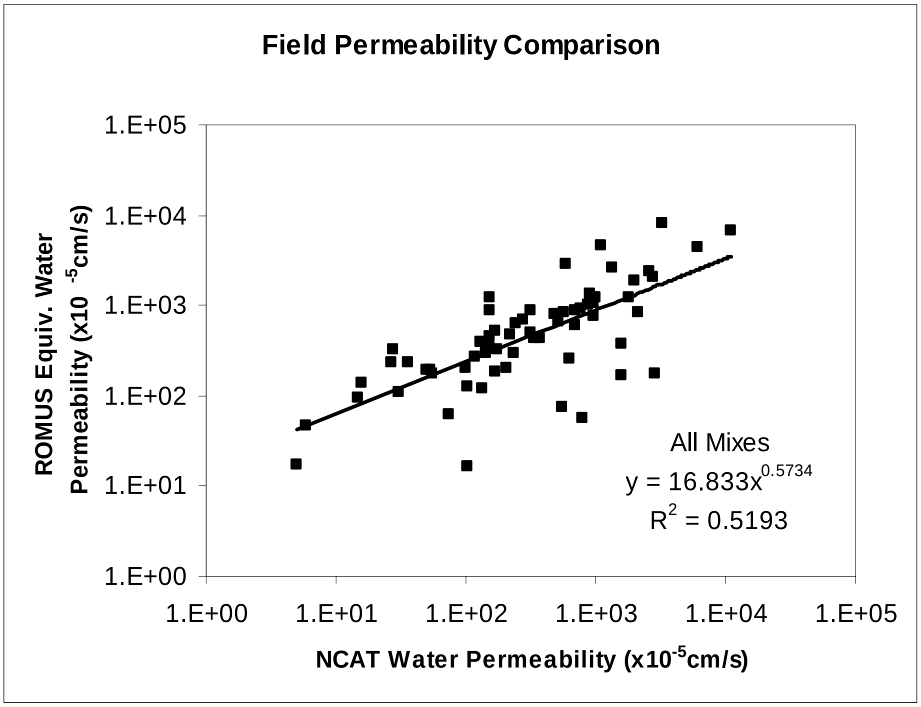


Figure 4.5 Aggregate Comparison of Field Permeability Readings

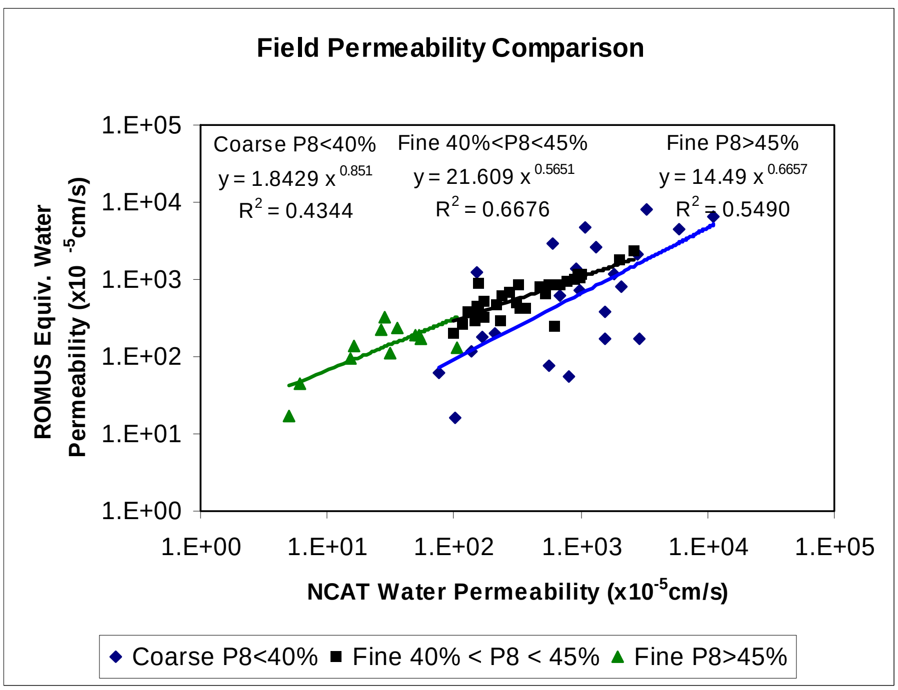


Figure 4.6 Group Comparisons of Field Permeability Readings

The data displayed in Figure 4.6 indicates better agreement between permeability devices for fine graded mixes with P8 > 40%.   Figure 4.7 provides a field permeability comparison for all fine mixes investigated.

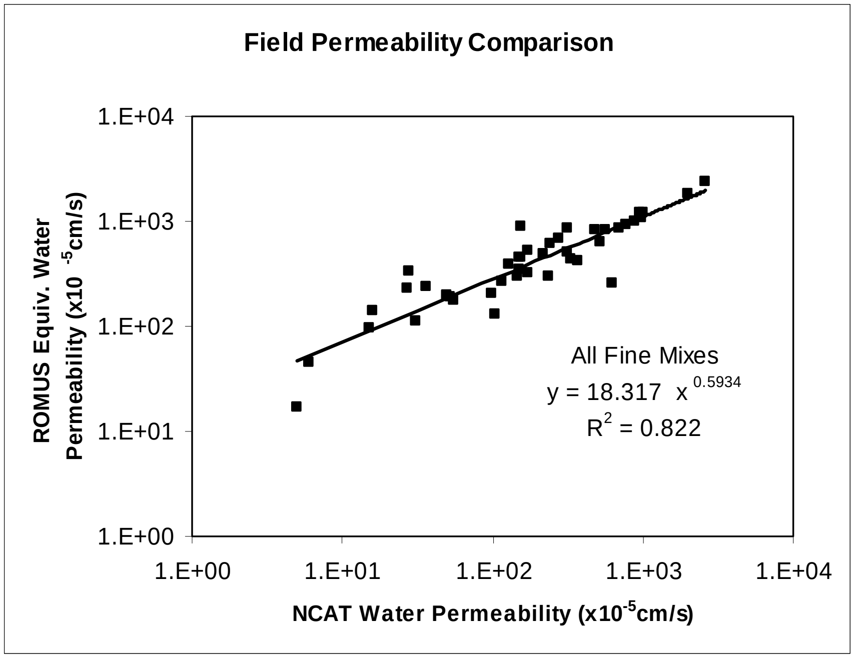


Figure 4.7 Field Permeability Comparison for All Fine Mixes

It is recognized that the data set used in the above comparison plots is limited; however, it appears that the ROMUS air permeameter may be well suited to serve as an alternate field testing device for measuring in-place permeabilities of asphalt pavement layers.

4.3 Preferential Flow Path Testing

Field and laboratory permeability measurements of asphalt pavements are directly related to the number, size, and interconnectivity of void pathways within the test sample. Correlations between field and laboratory water permeability readings described in Section 3.4.2 indicated laboratory measures typically produce permeabilities significantly lower than field obtained values. In an effort to more fully investigate the effects of preferential void pathways on measured permeabilities, a void pathways indicator was developed to better quantify the distribution of void pathways in compacted asphalt layers. This device was developed based on research findings presented by Hall and Ng (2001) with modifications to provide quantitative, rather than qualitative results on recovered asphalt cores or gyratory compacted samples.

The void pathways indicator developed during this research effort consists of a one-inch diameter water standpipe, ballast weights, isolation plates, and collection tubing. Figure 4.8 provides a schematic illustration of this device and Figure 4.9 illustrates the device as set up during testing. Tests were conducted on vacuum saturated core specimens after sandblasting of the perimeter wall was completed to remove any residual coring smear. For all tests, isolation plates were position at the top and bottom of the cores to segregate water exiting at the top and perimeter surfaces, respectively, from that which traveled vertically through the core specimen. For thicker cores in excess of 7 cm, an addition isolation plate was positioned at the mid-depth of the core to segregate upper and lower perimeter exit water. Individual core tests typically utilized three fillings of the standpipe to provide sufficient water collections at each exit location.

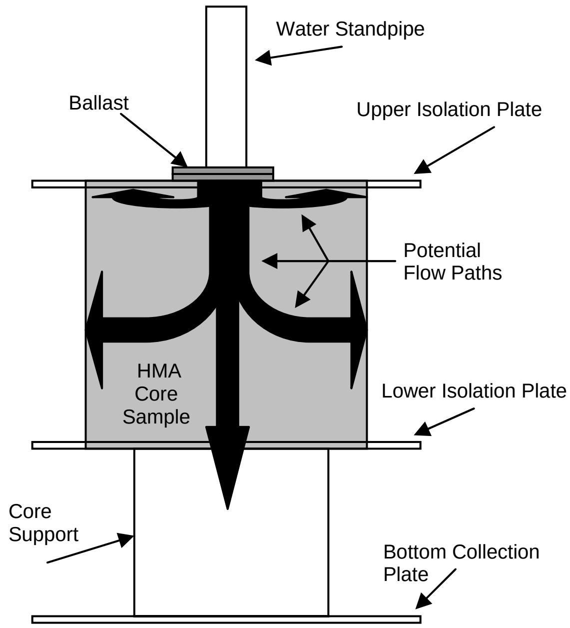


Figure 4.8 Schematic Illustration of the Void Pathways Indicator

Figure 4.9 Illustration of the Void Pathways Indicator Test Setup

Void pathways test results indicate a wide variation in preferential water pathways. Figures 4.10 and 4.11 illustrate the percentage of exit water which traveled vertically through the core specimens versus core thickness and core density, respectively. This parameter is of particular importance during comparisons of field and laboratory permeability measurements as cores which exhibit preferential vertical water flow should be more likely to produce comparable results between field permeability measures, which do not constrain directional water flow, and laboratory measures which are set up to allow only vertical water flow through core specimens. This statement assumes, however, that vertical flow out of the in-place asphalt layer is not constrained by supporting pavement layers. The best-fit data trend illustrated in Figure 4.10 clearly indicates preferential vertical flow reduces as the core thickness increases. The data provided in Figure 4.11 shows poor correlations between core density and vertical flow preference for all but the midrange core thickness where increased density tends to reduce preferential vertical flow.

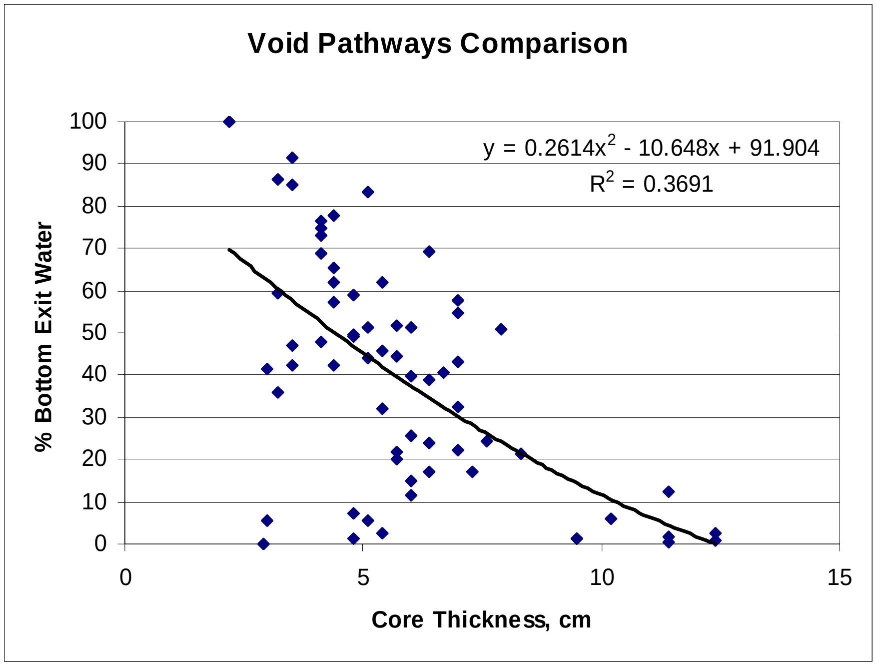


Figure 4.10 Void Pathways Comparison Based on Core Thickness

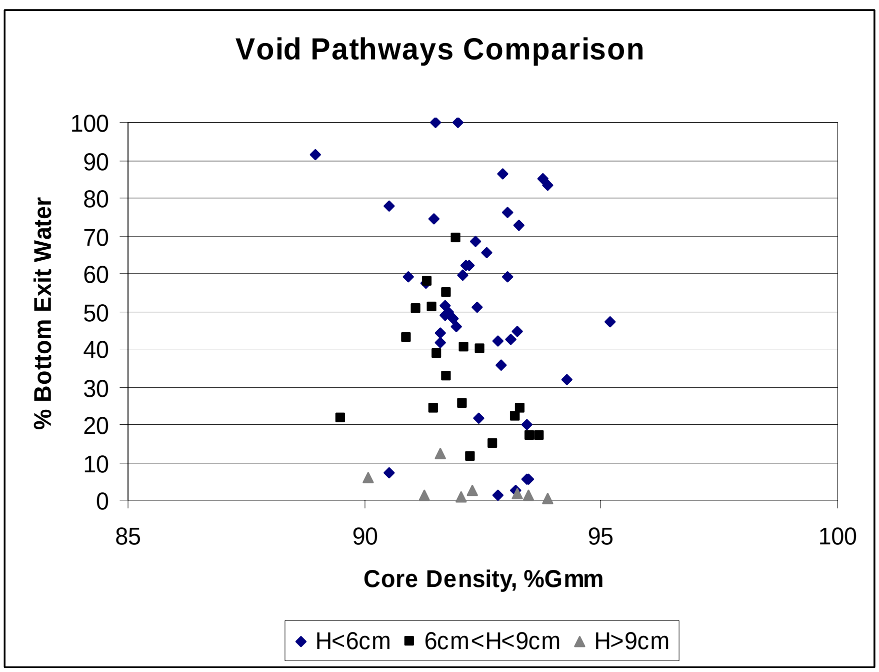


Figure 4.11 Void Pathways Comparison Based on Core Density

Figures 4.12 through 4.20 illustrate % bottom exit water versus core thickness, density and t/NMAS ratio for data segregated by mix gradation, aggregate type and NMAS. For coarse mixes with P8<40% (Figures 4.12 to 4.14) the % bottom exit water appears to be correlated only to core thickness with % bottom exit water reducing as thickness increases. For fine mixes with 40%<P8<45% (Figures 4.15 to 4.17) the % bottom exit water appears to be influenced by both core thickness and t/NMAS ratio with the % bottom exit water reducing as core thickness and t/NMAS ratio increase. For the fine mixes with P8>45% (Figures 4.18 to 4.20) the % bottom exit water appears to be influenced only by the t/NMAS ratio which reduces % bottom exit water as t/NMAS increases, particularly for the gravel source mixes.

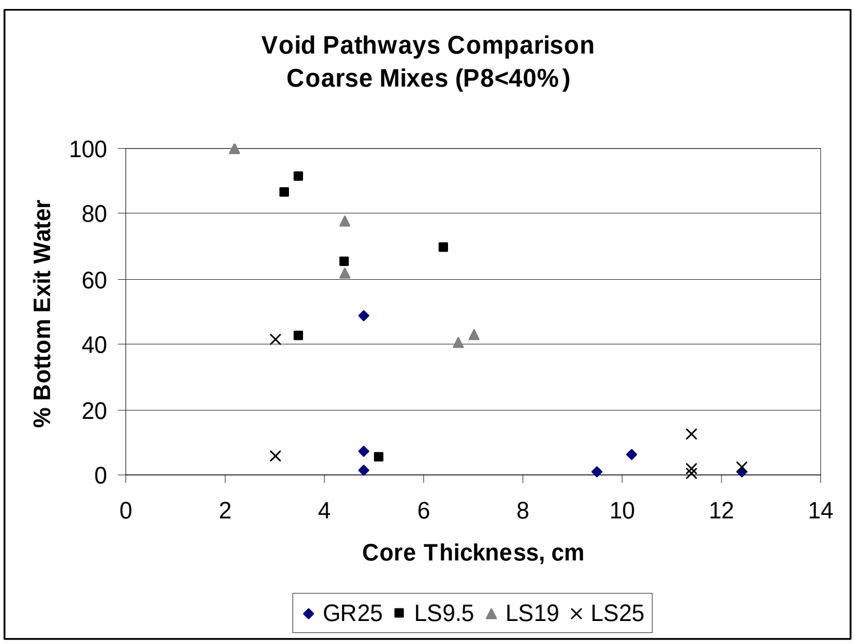


Figure 4.12 Void Pathways of Coarse Mixes Based on Core Thickness

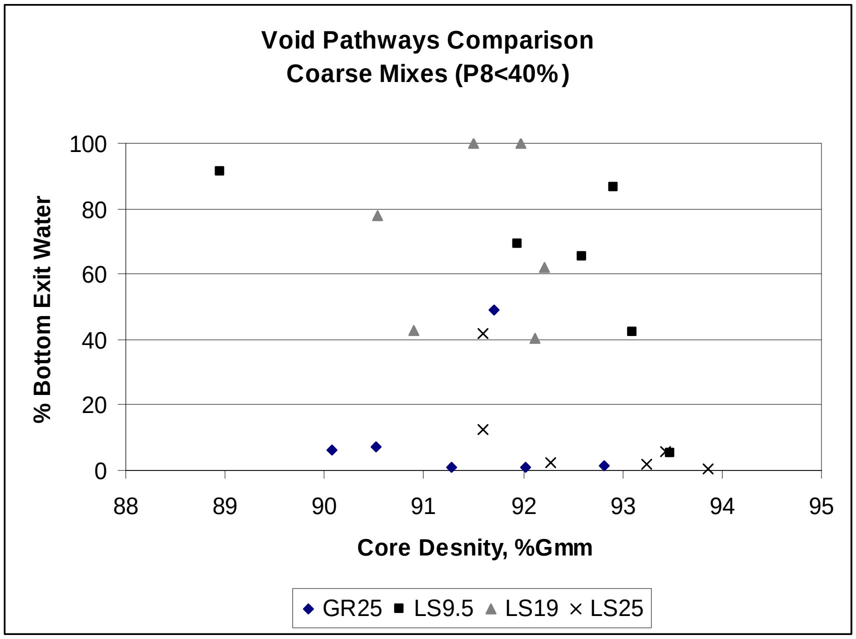


Figure 4.13 Void Pathways of Coarse Mixes Based on Core Density

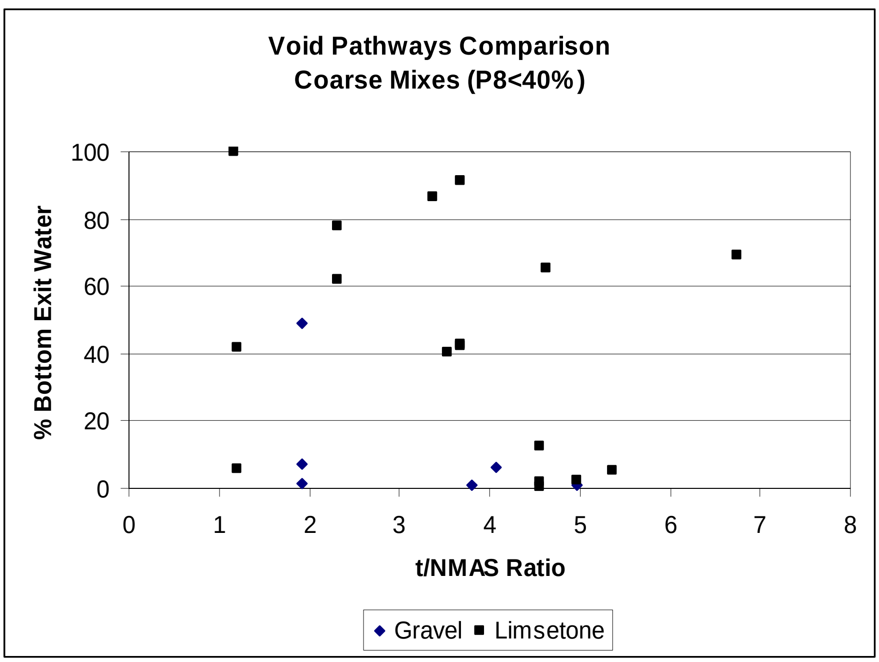


Figure 4.14 Void Pathways of Coarse Mixes Based on t/NMAS Ratio

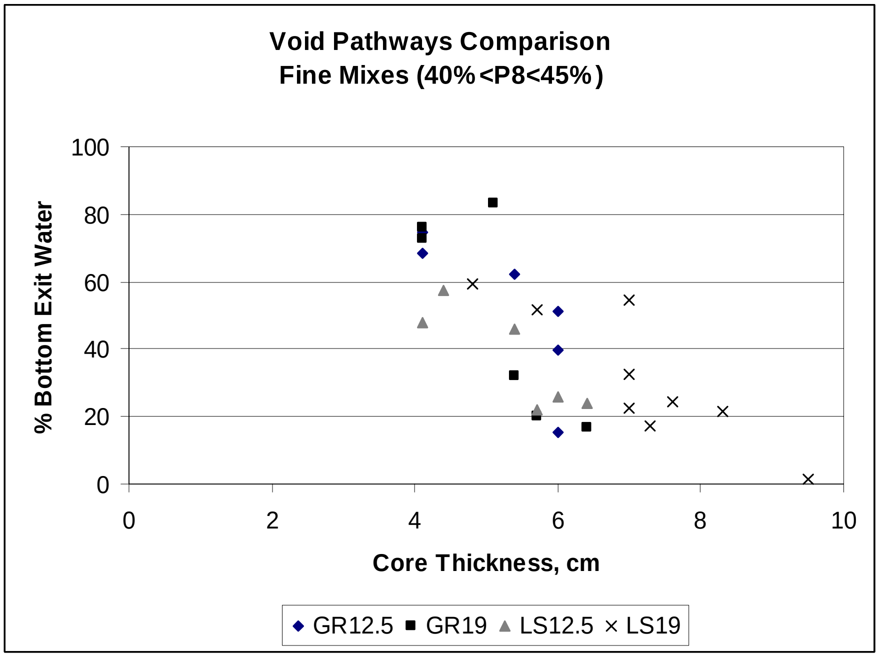


Figure 4.15 Void Pathways of Midrange Fine Mixes Based on Core Thickness

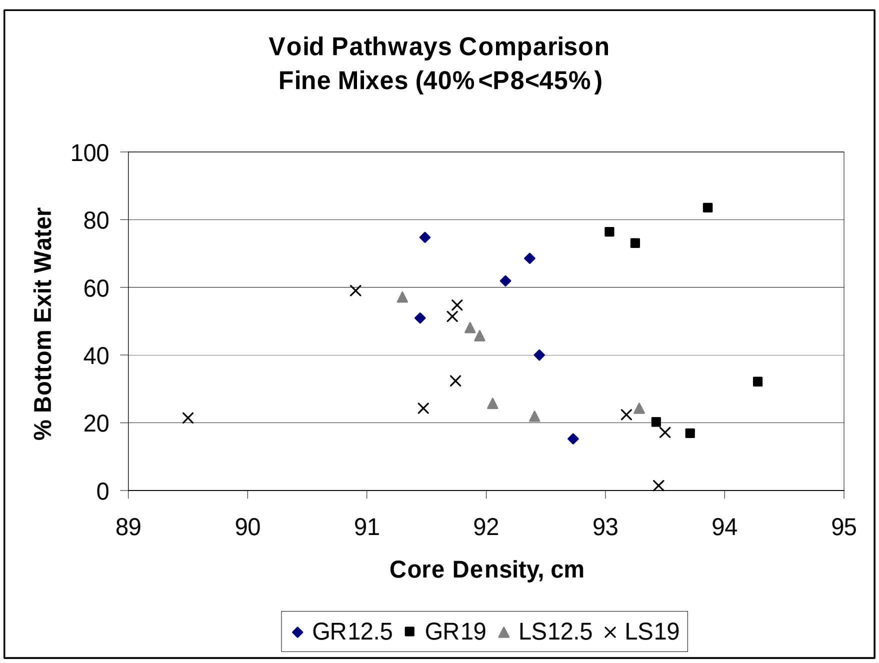


Figure 4.16 Void Pathways of Midrange Fine Mixes Based on Core Density

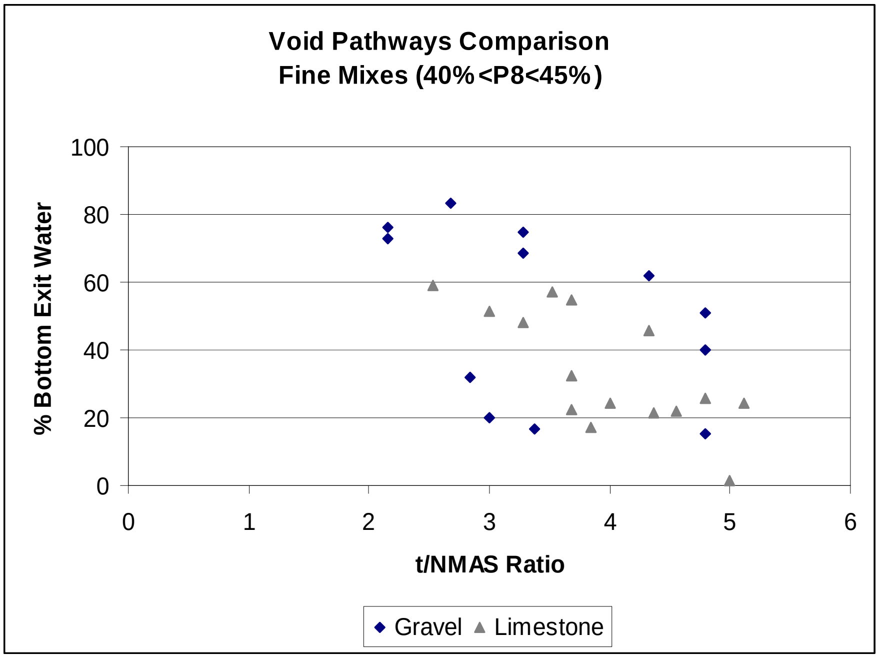


Figure 4.17 Void Pathways of Midrange Fine Mixes Based on t/NMAS Ratio

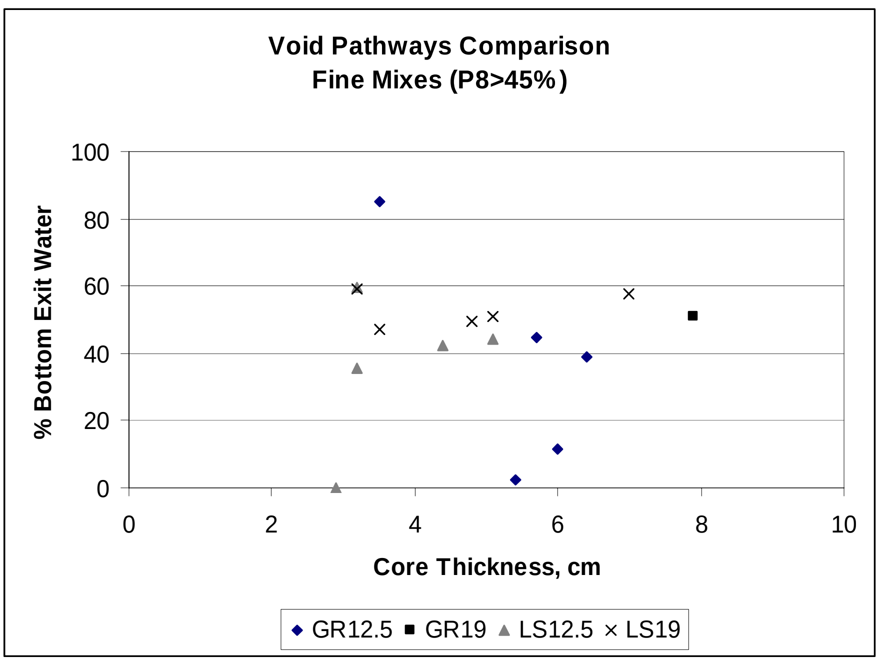


Figure 4.18: Void Pathways of Fine Mixes Based on Core Thickness

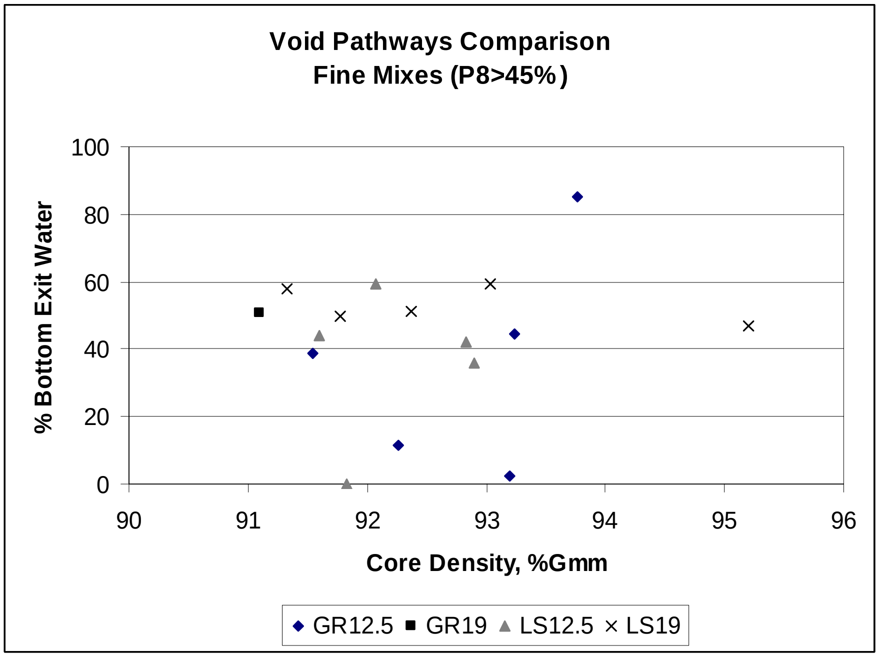


Figure 4.19 Void Pathways of Fine Mixes Based on Core Density

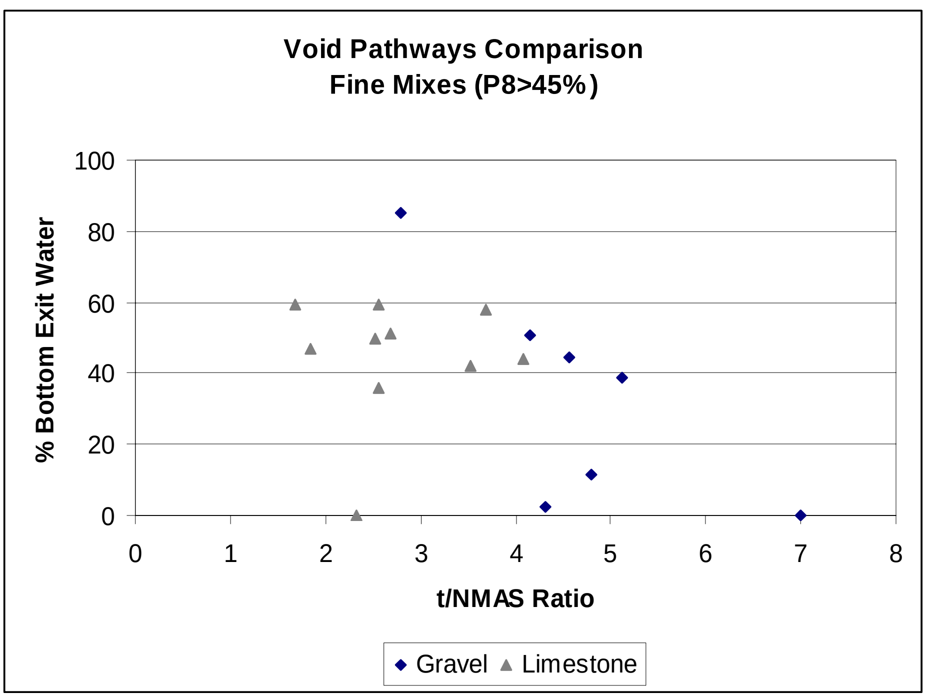


Figure 4.20 Void Pathways of Fine Mixes Based on t/NMAS Ratio

The impact of preferential vertical pathways on comparative field and laboratory water permeability measures was also examined. Figure 4.21 illustrates a comparison of measured water permeability ratios, calculated as the ratio of field permeability to lab permeability, versus % bottom exit water for all cores tested. On this aggregate level, no discernable trend is evidenced.

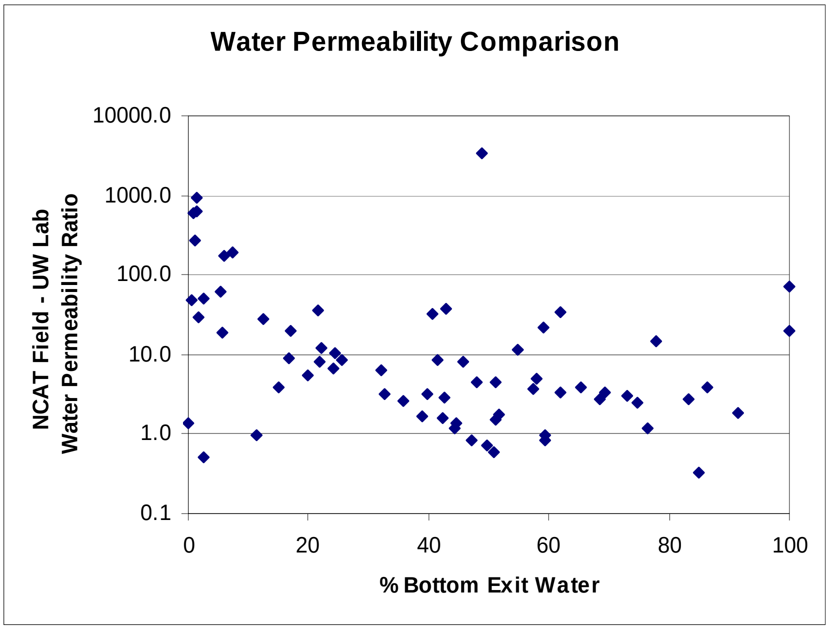


Figure 4.21 Water Permeability Comparison Based on Void Pathways

Figures 4.22 to 4.24 illustrate water permeability ratios versus % bottom exit water for mix types segregated by the P8 percentage. For the coarse (P8<40%) and midrange fine (40%<P8<45%) gradations, the water permeability ratios tend to decrease as the % bottom exit water increases (Figures 4.22 and 4.23). For the coarse mixes, the best-fit trend line suggests that even for cores with a high degree of vertical flow preference (% bottom exit water > 80%) field and lab permeability values may differ by an order of magnitude. In contrast, the trend line for the midrange fine gradations indicates better agreement between field and lab permeability measures as preferential vertical flow increases.

For fine mixes with P8>45%, the water permeability ratio does not appear to be affected by preferential vertical pathways as the available data indicates permeability ratios near unity for all cores examined.

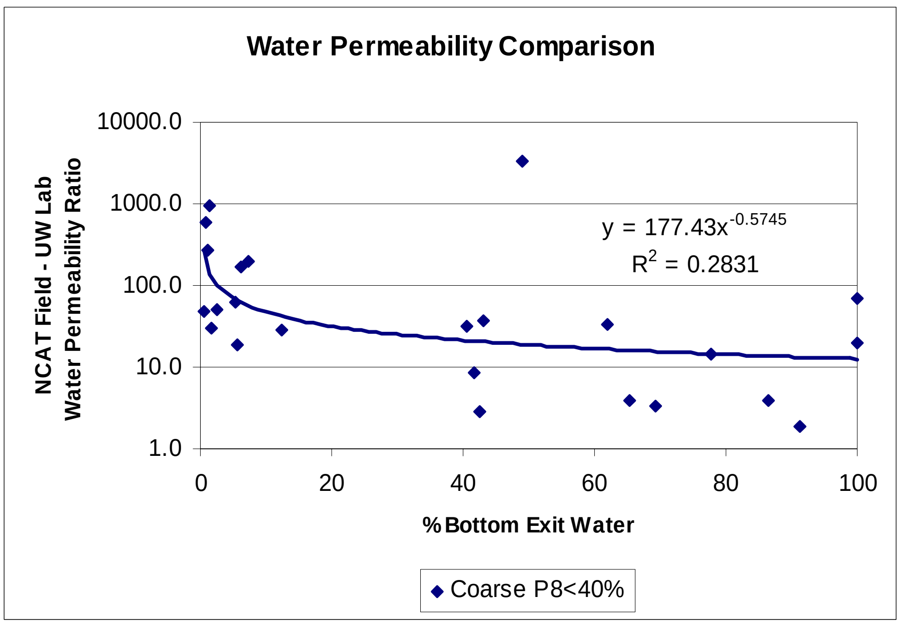


Figure 4.22 Water Permeability Comparison for Coarse Mixes

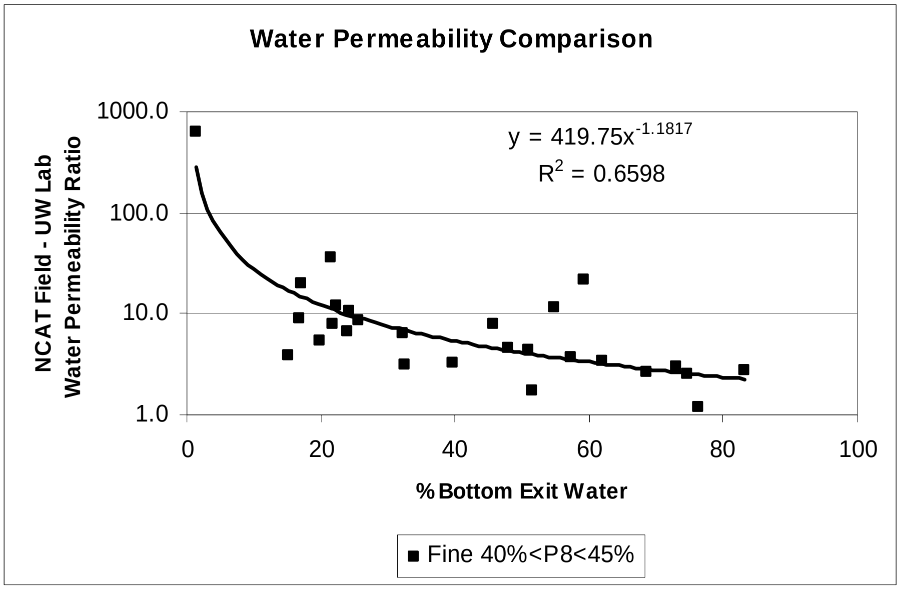


Figure 4.23 Water Permeability Comparison for Midrange Fine Mixes

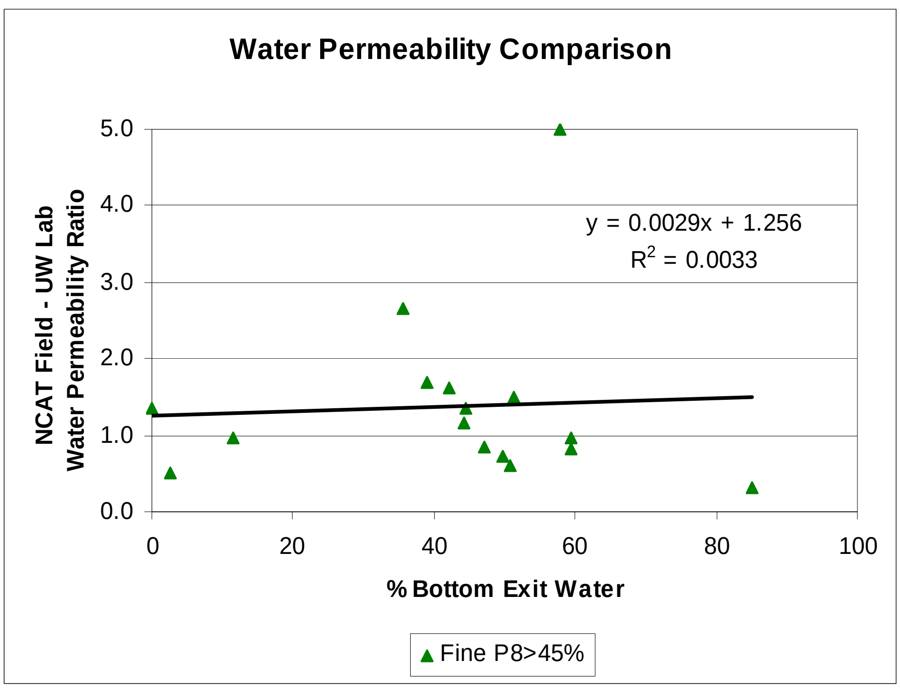


Figure 4.24 Water Permeability Comparison for Fine Mixes

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Findings

5.1.1 Field Study

Based on an analysis of the data collected in the field study, the following findings can be stated:

1) Density and permeability characteristics of Superpave mixes are based on project-specific variables. Base type, source, gradation, and Ndes level all influence field density and permeability. No discernible trend was observed between density and permeability for coarse-graded mixes.
2) A clear relationship between layer thickness and permeability was not established. Layer thickness was a factor on a project-specific basis, with some projects indicating it was significant, while others found it not significant.
3) Fine-graded limestone-source mixes compacted on PCC, and those designed at a higher Ndes level, were more permeable than other mixes produced from different sources or constructed on different subsurface layers.
4) For fine-graded mixes, the t/NMAS ratio showed an influence on achieving density, particularly below a ratio of 2 for gravel-source mixes and a ratio of 3 for limestone-source mixes. For limestone-source mixes outside the current WisDOT t/NMAS range of 3 to 5, it was more difficult to achieve density below a ratio of 3, and possible to achieve a 92% density above a ratio of 5. No clear relationship was found between t/NMAS ratios and permeability.

5) For coarse-graded mixes, mixes compacted at smaller t/NMAS ratios for limestone-source were more permeable than higher ratios, but no trend was observed for the gravel-source mix.
6) The factors that affected density growth during compaction included mat temperature, number of passes, and their interaction (a declining mat temperature occurs with more passes).
7) It is found that gradation of the aggregate could be linked to permeability. The ratio of (%P1/2 - %P3/8) / (%PNo.4-%PNo.8) had a good correlation with permeability with high ratios showing lower permeability. In addition, higher permeability was measured as the gaps increase between the coarse aggregates (%P1/2" and %P3/8") and/or the fine aggregates (%P4 and %P8). This suggests that relative differences in these sieves may have an effect on internal void structure, and thus measured permeability, of the compacted material. This trend could be used in mix design by controlling the ratio to limit permeability by either reducing the difference between the coarse sieves, fine sieves, or both.
8) The air permeameter produced results which were comparable to those obtained with the NCAT water permeameter, particularly for the fine-graded mixes. The initial results show that the air permeameter produces time efficient, reproducible results and appears to be a viable alternative for the NCAT water permeameter.

5.1.2 Laboratory Study

Based on the analysis of data collected in the laboratory study, the following findings can be stated:

1) A good relationship exists between the density measured by using the nuclear gauge and the density measured in the lab using the Corelok Device. The nuclear gauge has therefore been found to be a rapid, reliable, and non-destructive method to accurately measure in-place density of asphalt mixtures in the field.

2) The NCAT field permeability device was found to give results that sometimes compares well to laboratory measurements done on field cores but not always. For fine-graded mixture with P8 higher than 45%, field permeability measured by the NCAT device strongly correlates to laboratory permeability measured on field cores taken from same pavements section. However, the relationship is not one to one ratio. The field permeability values could be approximately an order of magnitude higher than the lab permeability. This could be explained by the multiple flow directions in the field permeability measurement. The coefficients of correlation for the mathematical relationship found is high (R^2 = 0.80). This indicates that the NCAT permeability devices, with all its limitations, could be used in the field for fine-graded mixture (with P8 > 45%) to measure an index of permeability reliability. The measured values can then be related to true permeability of field cores measured by the ASTM D5084 conducted under well-controlled conditions. There is a concern, however, in using the NCAT device for measuring the field permeability of mixtures with P8 lower than 40%, since very poor correlation was found for the relationship between field and lab permeability in this study. The modification of NCAT device is therefore necessary in order to prevent water leakage along the sealant due to rough pavement surface, particularly for mixtures with coarse gradation.

3) A method was developed to compact specimens in the SGC at various sample sizes that could be used to estimate relatively well the permeability of the specimens taken out from pavements in the field. The permeability measured on these SGC specimens correlates to the permeability measured on the field cores with a relationship of one to one. Therefore, this method (called in the report Method B) could be used for predicting the permeability of asphalt mixtures in the field. If this method can be validated, then the permeability can be included as a design requirement.
4) A method, and related equipment, were developed for quantifying the preferential void pathways in compacted asphalt layers. The degree of vertically connected void pathways was found to be best correlated to the pavement layer thickness, with greater thicknesses producing a reduction in preferential vertical void pathways. Correlations between field/lab water permeability ratios and preferential vertical void pathways indicate that field and laboratory permeability values can only be expected to be in near agreement when the degree of preferential vertical void pathways exceeds 80% for fine mixes. For coarse mixes with a high degree of preferential vertical void pathways, field/lab water permeability ratios of 10 or more may be expected.

5.2 Recommendations

5.2.1 Guidelines for Selection of Pavement Thickness in Wisconsin

It is recommended that no changes be made to the current layer thickness values and t/NMAS ratios in the specifications. Density and permeability characteristics of

Superpave mixes are found to depend on several project-specific variables, such as base type, source, gradation, Ndes level, layer thickness, and t/NMAS ratio. No compelling evidence is found in the data to alter layer thickness and t/NMAS ratios, without accounting for the other remaining project-specific variables. It is however important to recognize that the current recommendations do not ensure achieving density nor limit permeability. Difficulty in achieving density or exceeding acceptable permeability is influenced by several interacting factors.

5.2.2 Recommendations on Laboratory and Field Permeability Testing Procedure

To measure laboratory permeability and estimate field permeability, the following testing procedure is recommended for the mixture design and quality control of Superpave mixtures in Wisconsin. Figure 5.1 shows the detail steps required for the procedure using samples compacted in the laboratory.

1) Evaluate the job mix formula to determine if the mix is fine or coarse graded and determine the percent passing the No. 8 sieve.
2) For fine graded mixes with P8>45%, produce Superpave gyratory compacted (SGC) specimens from representative loose materials according to Method B described in this report.
3) Measure the true permeability of the SGC specimens in the laboratory according to ASTM D5084.
4) Estimate the lab and field permeability of the field compacted specimens based on the target field density using the relationship between lab permeability and density derived from testing the samples with different sizes.

5) For fine-graded mix with P8 < 45%, and for coarse-graded mix, the lab permeability cannot be used to estimate field permeability because there is no correlation between the field permeability, which includes flow in multiple directions, and the one-dimensional permeability measured in the lab on a sample compacted in the SGC. To estimate the true one-dimensional permeability a core should be extracted and used for measuring permeability in the lab.

6) For quality control purposes of fine graded mixes with (P8 > 45%), the NCAT device can be used to measure an index of permeability in the field. The actual (one dimensional) permeability can be predicted using the following equation. The estimated value can be compared to the design permeability value.

   - For fine-graded mix (P8 > 45%)

     $$\text{Field K} = 8.34 \times e^{0.055\ (\text{Lab K})}$$

   For other types of mixtures, the NCAT device can be used as a quality control.

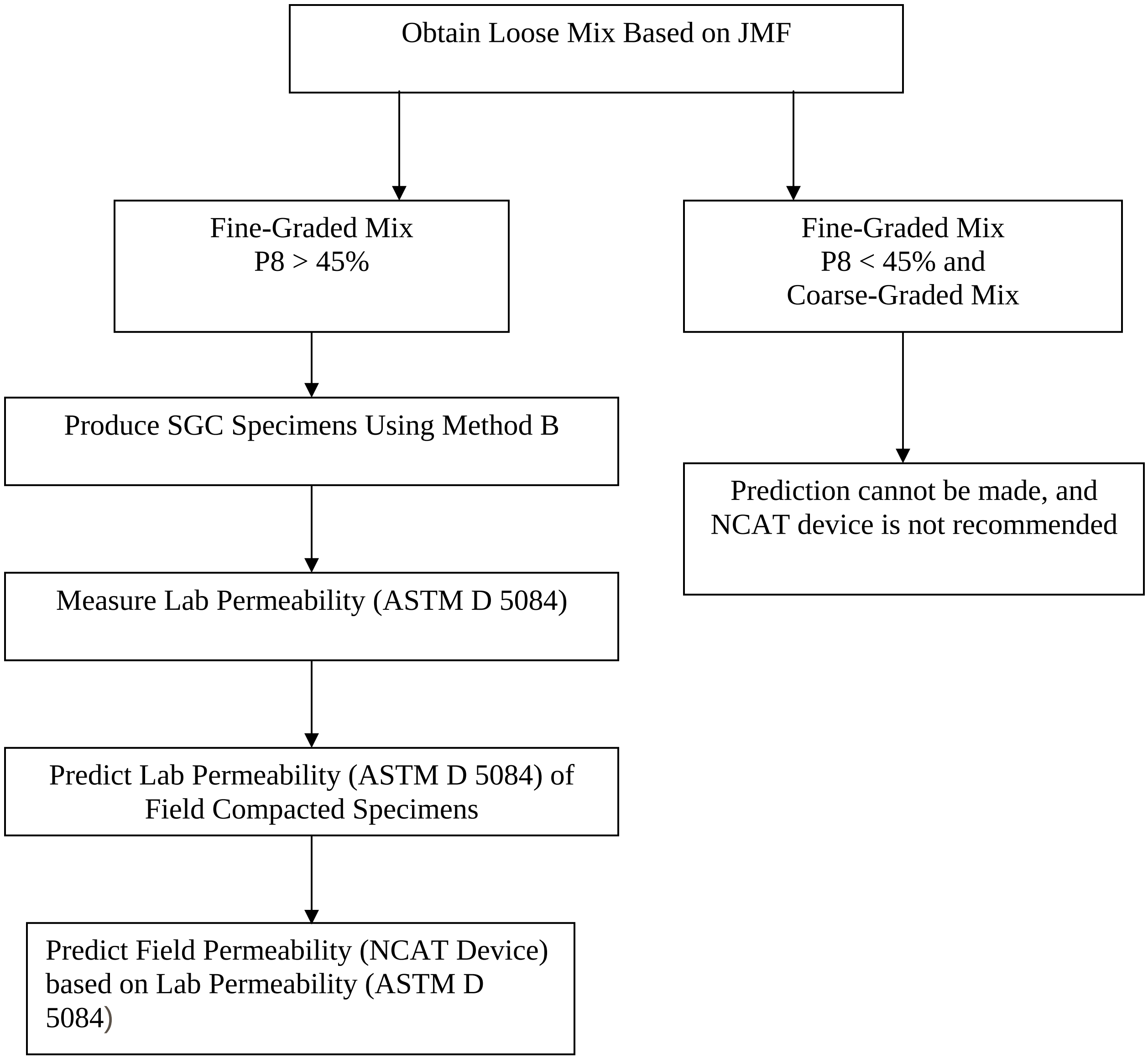


Figure 5.1 Procedures for designing and predicting field permeability

5.2.3 Recommendations for Permeability and Density Criteria for Superpave Mix Designs in Wisconsin

It is recommended that target permeability and density values ultimately be established from in-service pavements with recorded performance histories. One such group of pavements includes accepted warranty projects that have been in service for 5 or more years. Field permeability and density measures on these pavements can aid in the development of acceptance values that correlate to good performance.

Until a performance-based determination is made, an interim approach is recommended that establishes the minimum acceptable density based on median permeability values. Based on research data included in this report for fine-graded Superpave mixes, a specified minimum density of 93.8% would be required to limit permeability to 150×10^{-5} cm/sec. For coarse-graded Superpave mixes, the research data does not support the establishment of minimum acceptable densities to control permeability because of the lack of a unified relationship between density and permeability that is independent of source or garadtion of mixtures. The limit should remain at 150×10^{-5} cm/sec but should be measured directly on a core recovered from pavement section.

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Appendix A

Project-Specific Permeability Significance Testing

Table A.1 ANOVA Results of Project Significance Testing (Fine Mixes)

Variable (1)	I-43 19-mm Limestone Coarse (2)	STH-23 19-mm Gravel Fine (3)	STH-23 12.5-mm Gravel Fine (4)	USH-18 19-mm Limestone Fine (5)	USH-18 12.5-mm Limestone Fine (6)	USH-10 19-mm Limestone Fine (7)	USH-10 12.5-mm Limestone Fine (8)
Degrees of Freedom	14	22	11	31	17	20	13
Thick	***	***	***	N/S	N/S	***	N/S
Density	N/S	***	**	***	***	*	*
Thick*Density	N/S	***	N/S	N/S	N/S	N/S	N/S
Testing Variability, %	29	5	23	70	56	37	67
Significance Levels: N/S = Not Significant; * = 0.05 < p-value < 0.10 ; ** = 0.01 < p-value< 0.05; *** = p-value < 0.01							

Table A.2 ANOVA Results of Project Significance Testing (Fine Mixes)

Variable (1)	I-894 19-mm Limestone Fine (2)	I-894 12.5-mm Limestone Fine (3)	STH-21 19-mm Limestone Fine (4)	STH-21 12.5-mm Limestone Fine (5)	USH-8 19-mm #1 Gravel Fine (6)	USH-8 19-mm #2 Gravel Fine (7)	USH-8 19-mm pooled Gravel Fine (8)	USH-8 12.5-mm Gravel Fine (9)
Degrees of Freedom	16	11	16	22	16	18	35	17
Thick	N/S	N/S	***	***	***	*	N/S	***
Density	***	***	***	***	N/S	N/S	N/S	N/S
Thick*Density	N/S	**	**	***	N/S	N/S	N/S	N/S
Testing Variability, %	15	2	5	8	41	82	87	51
Significance Levels: N/S = Not Significant; * = 0.05 < p-value < 0.10 ; ** = 0.01 < p-value< 0.05; *** = p-value < 0.01								

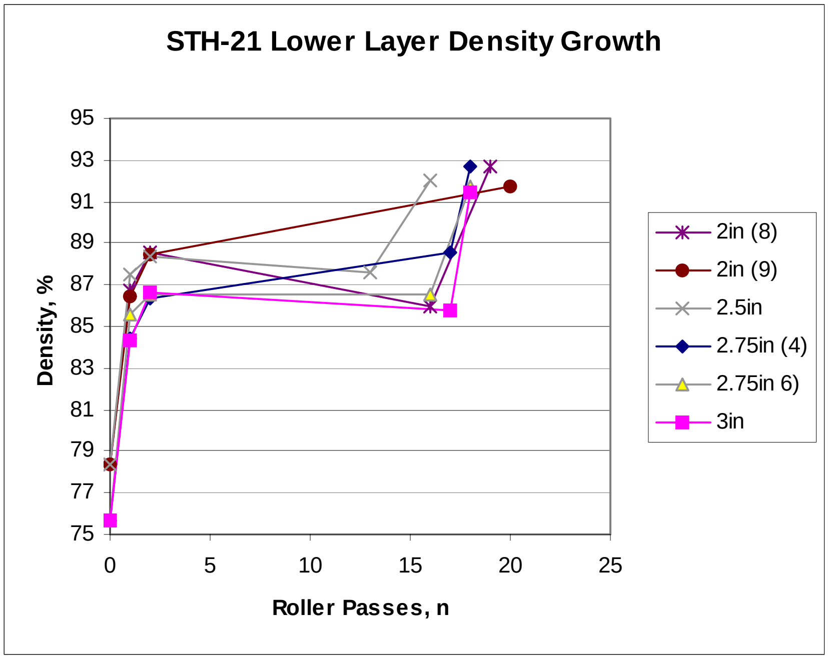
Table A.3 ANOVA Results of Project Significance Testing (Coarse Mixes)

Variable (1)	I-94 25-mm Limestone Coarse (2)	USH-20 19-mm Limestone Coarse (3)	USH-20 9.5-mm Limestone Coarse (4)	STH-17 25-mm Gravel Coarse (5)
Degrees of Freedom	15	11	11	15
Thick	N/S	***	***	**
Density	N/S	***	*	***
Thick*Density	N/S	***	N/S	**
Testing Variability, %	73	1	2	13

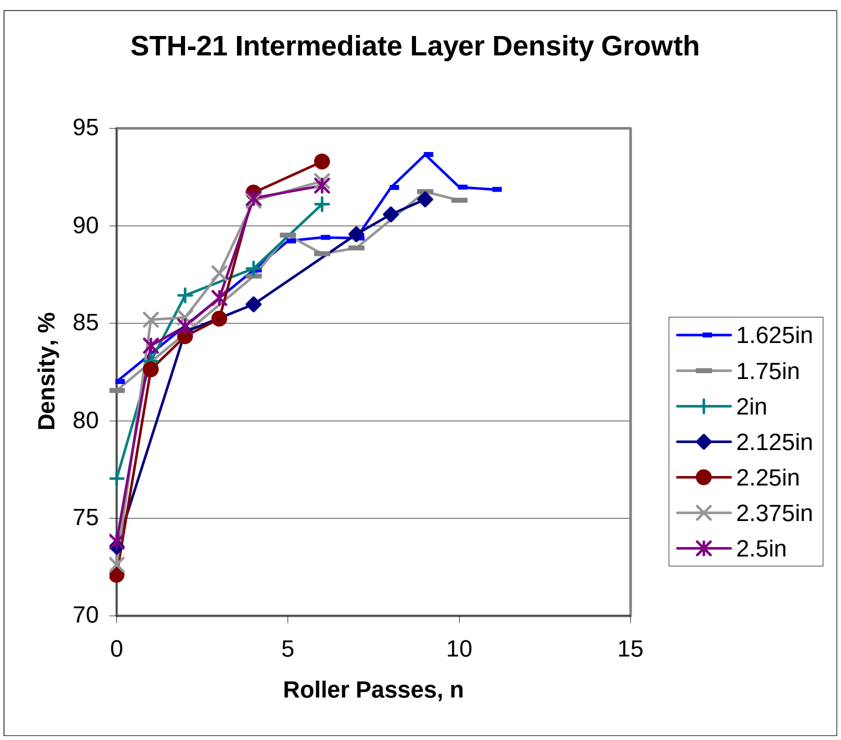
Significance Levels: N/S = Not Significant; * = 0.05 < p-value < 0.10 ;
** = 0.01 < p-value< 0.05; *** = p-value < 0.01

Appendix B

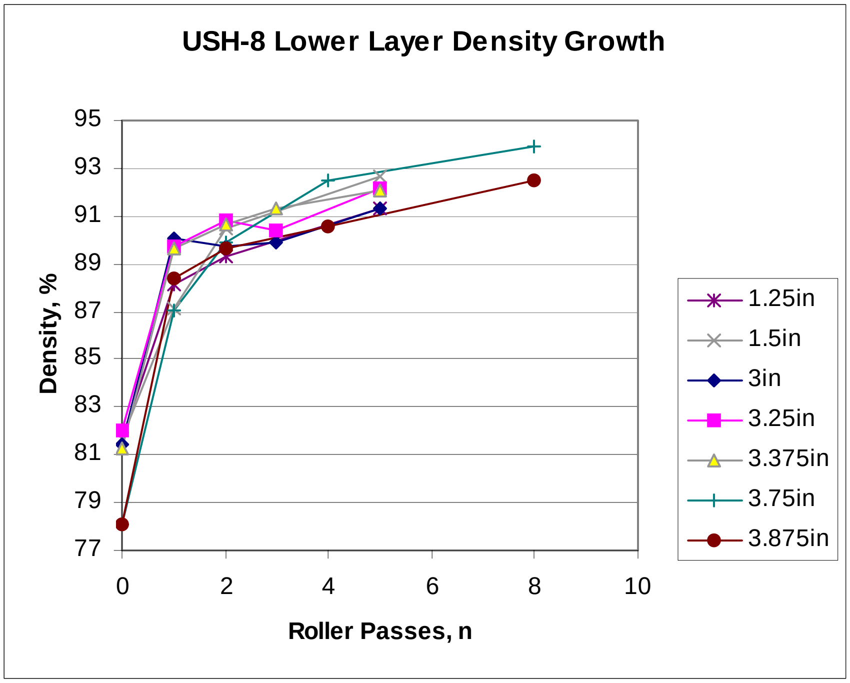
Density Growth Plots



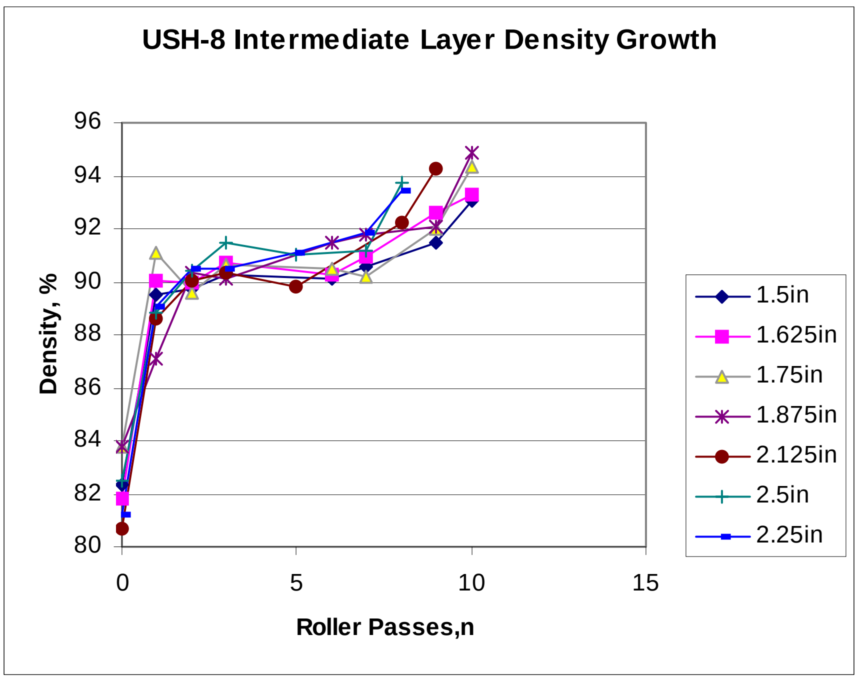
B.1 Density Growth on STH-21 19-mm Lower Layer Mix



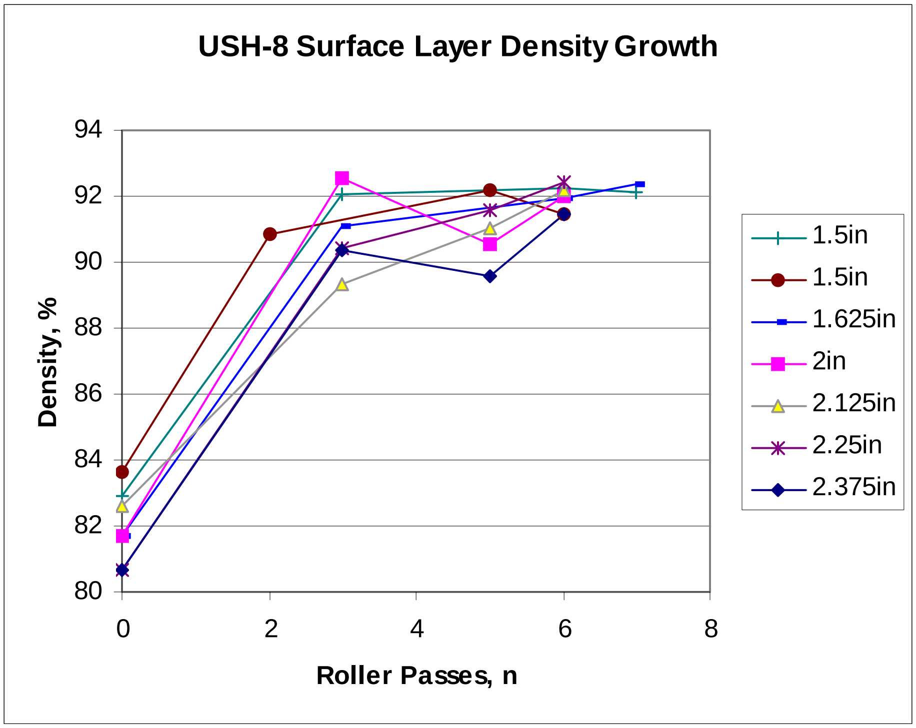
B.2 Density Growth on STH-21 12.5-mm Lower Layer Mix



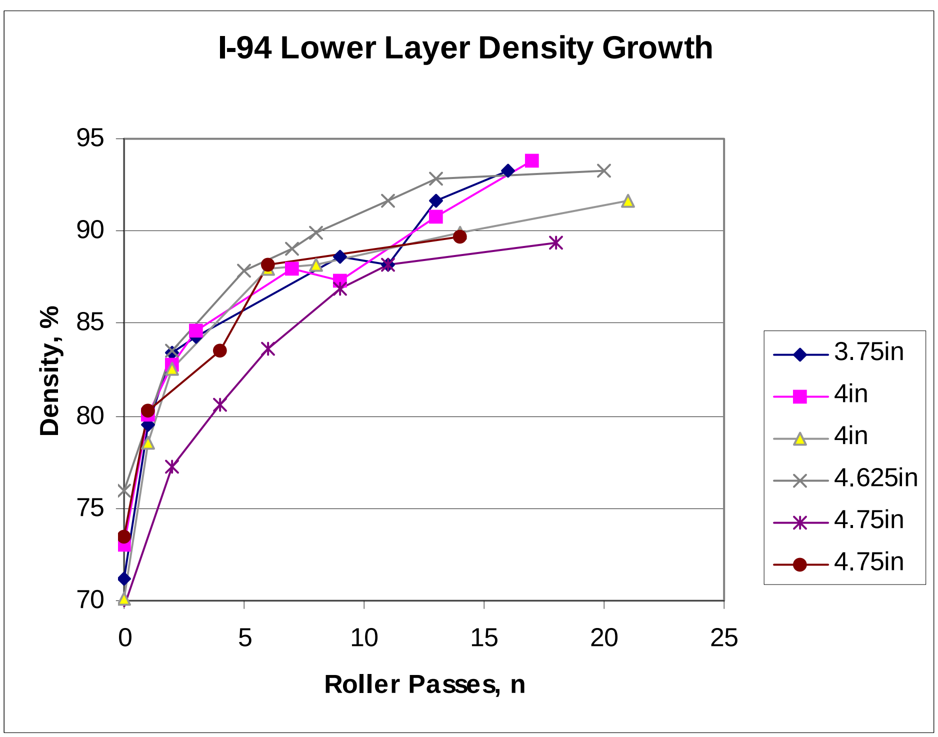
B.3 Density Growth on USH-8 19-mm Lower Layer Mix



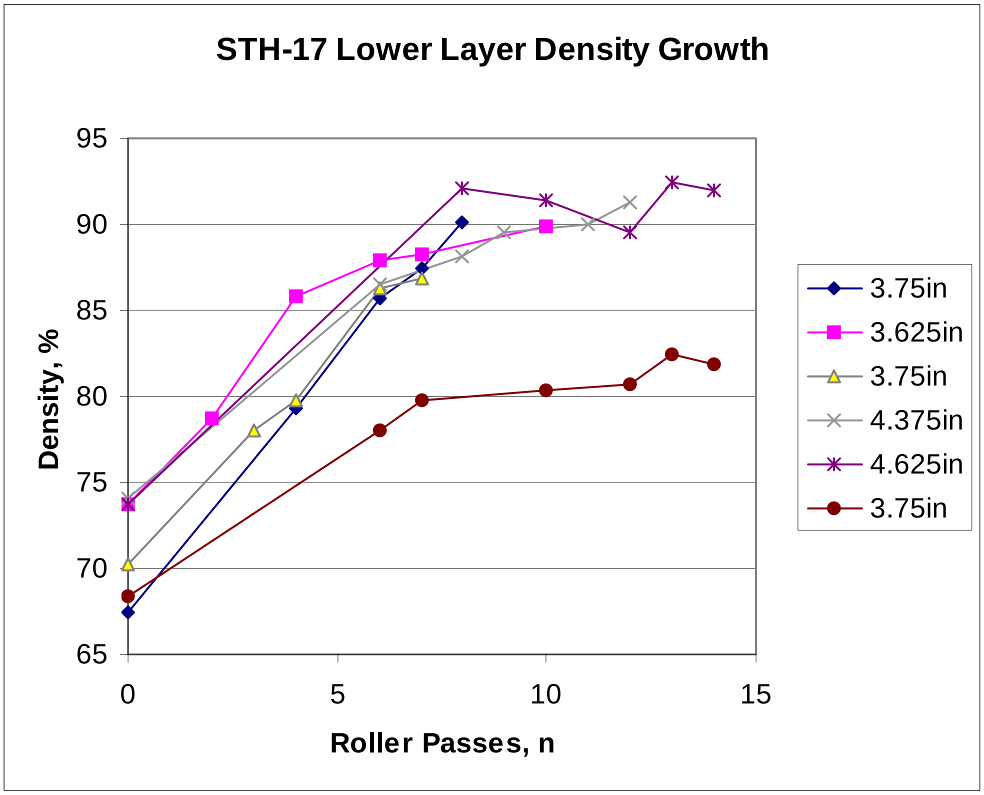
B.4 Density Growth on USH-8 19-mm Intermediate Layer Mix



B.5 Density Growth on USH-8 12.5-mm Surface Layer Mix



B.6 Density Growth on I-94 25-mm Lower Layer Mix



B.7 Density Growth on STH-17 25-mm Lower Layer Mix